Evaluation of Solid Residues from Atmospheric Fluidized Bed Combustion, 1984/85

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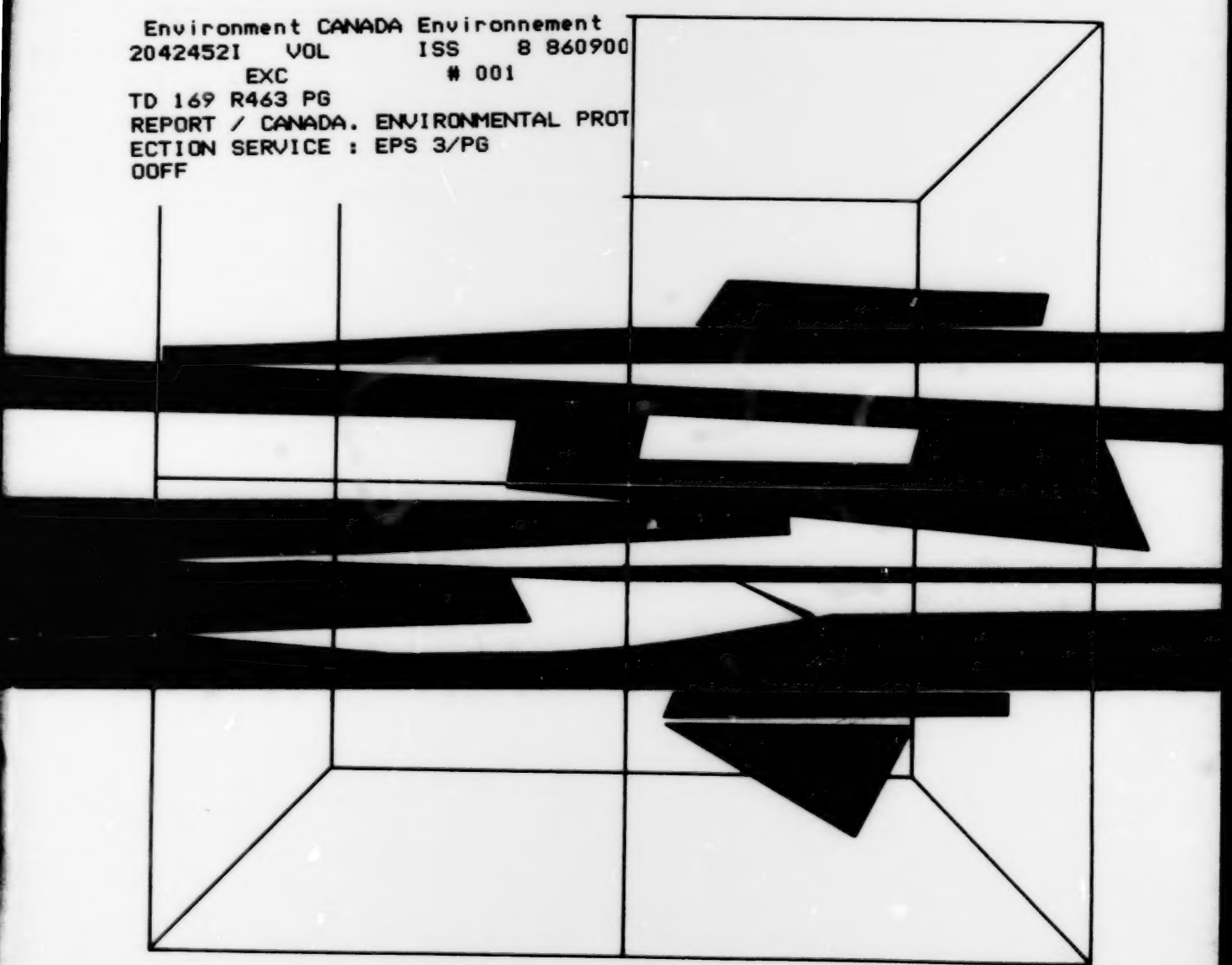

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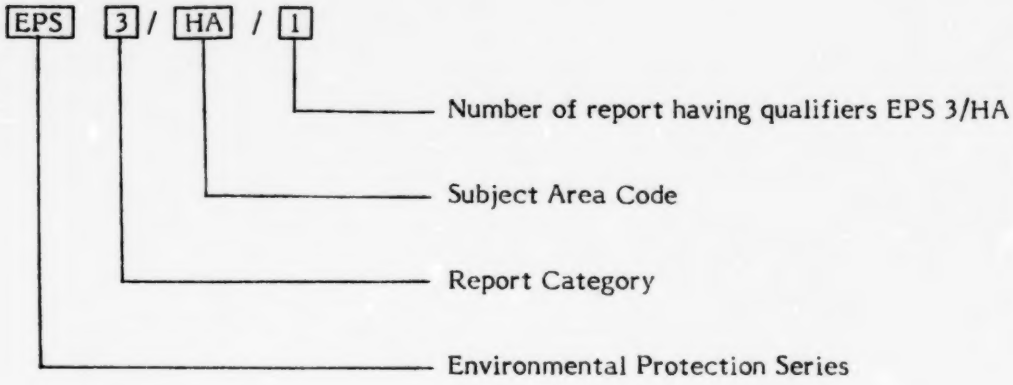

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EVALUATION OF SOLID RESIDUES FROM ATMOSPHERIC FLUIDIZED BED COMBUSTION, 1984/1985

by

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READERS COMMENTS

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ABSTRACT

A series of tests and analyses were conducted on solid residues from two Canadian atmospheric fluidized bed combustion (AFBC) installations: the Queen's University pilot-scale unit; and the full-scale demonstration unit at Canadian Forces Base Summerside, P.E.I. Both units utilize eastern Canadian high sulphur bituminous coals for fuel and eastern Canadian limestone as the sulphur sorbent. Most tests and analyses were similar to those used in two previous studies to characterize the physical, chemical, exothermic and leaching properties of AFBC solid wastes produced at coal-fired power generating stations. Additional tests were also employed to examine bulk density, unconfined compressive strength and column leaching.

In general, the results of this study confirmed the findings of the previous studies. The results of the column leaching tests and field observations at the Summerside disposal area, however, suggest reactions may continue to occur over several months until the residues eventually solidify. The leachability of these residues, therefore, may be overestimated if only conventional batch leaching tests are used.

The results indicate that the residues should be hydrated, dried (if necessary) to between 20% and 30% moisture, and compacted prior to final disposal in a landfill. This would delay the commencement of leachate release from the landfill, decrease disposal volume requirements, and decrease the leachate production rate. It would also allow the exothermic reactions in the residues to be completed prior to final placement.

RÉSUMÉ

Les résidus solides de deux installations canadiennes de combustion atmosphérique sur lit fluidisé (CALF): l'unité pilote de l'Université Queen et l'unité de démonstration en situation réelle de la base des forces armées canadiennes à Summerside, Î.-P.-É., ont fait l'objet d'une série d'essais et d'analyses. Ces deux installations utilisent comme combustible du charbon bitumineux à forte teneur en soufre provenant de l'est du Canada; le soufre est absorbé par de la pierre à chaux provenant de la même région. La plupart des essais et des analyses étaient les mêmes que ceux utilisés dans deux études précédentes pour déterminer les propriétés physiques, chimiques et exothermiques des déchets solides de la CALF et dans quelle mesure ils peuvent perdre leurs constituants par lixiviation. D'autres essais ont aussi été effectués pour déterminer la masse volumique apparente et la résistance à la compression sans étreinte latérale ainsi que pour étudier la lixiviation en colonne.

En général, les résultats obtenus ont confirmé ceux des études précédentes. Les essais de lixiviation en colonne indiquent toutefois que, dans le cas des matières épandues sur le sol et provenant du lit fluidisé et des dépoussiéreurs à sec filtrants, la lixiviation est beaucoup moins considérable que les essais en discontinu ne l'avaient prédit, probablement à cause des réactions pouzzolaniques dans les résidus, qui ont pour effet d'augmenter le volume de ces derniers et de les faire se solidifier.

Les résultats indiquent que les résidus devraient être hydratés, séchés au besoin pour que leur pourcentage d'humidité soit compris entre 20 % et 50 %, et compactés avant d'être finalement éliminés dans une décharge, ce qui aurait pour effet de retarder le début de la lixiviation, de réduire le volume des résidus et de diminuer le taux de lixiviation. En outre, les réactions exothermiques seraient terminées avant que les résidus ne soient mis en décharge.

TABLE OF CONTENTS

		Page
ABSTRACT		iii
RÉSUMÉ		iv
LIST OF FIGURES		vi
LIST OF TABLES		vii
1	INTRODUCTION	1
2	EXPERIMENTAL PROGRAM	5
2.1	Determination of Physical Properties	5
2.2	Determination of Chemical Properties	7
2.3	Determination of Exothermic Properties	8
2.4	Determination of Leaching Properties	9
3	RESULTS AND DISCUSSION	12
3.1	Physical Properties	12
3.1.1	Moisture Content	12
3.1.2	Compressive Strength	12
3.1.3	Permeability	14
3.1.4	Water Holding Capacity	16
3.1.5	Bulk Density	18
3.1.6	Expansion During Hydration	18
3.1.7	Moisture/Density Relationships	21
3.2	Chemical Properties	21
3.2.1	Residue Composition	21
3.2.2	Acid Neutralization Capacity	21
3.2.3	pH	27
3.3	Exothermic Properties	27
3.3.1	Calorimeter Tests	27
3.3.2	Column Exothermic Tests	31
3.4	Leaching Properties	36
3.4.1	Batch Leaching Tests	36
3.4.2	Column Leaching Tests	36
3.5	Quality Control	47
4	SUMMARY	48
REFERENCES		49
APPENDIX	TEST RESULTS	51

LIST OF FIGURES

Figure		Page
1	BULK DENSITIES OF BED MATERIALS	19
2	BULK DENSITIES OF BAGHOUSE MATERIALS	20
3	RESULTS OF MOISTURE/DENSITY TESTS	22
4	ACID NEUTRALIZATION CAPACITY VERSUS CALCIUM CONTENT	28
5	ACID NEUTRALIZATION CAPACITY VERSUS SULPHUR CONTENT	29
6	HEAT OF REACTION VERSUS ACID NEUTRALIZATION CAPACITY	32
7	RESULTS OF COLUMN EXOTHERMIC TESTS ON SUMMERSIDE MATERIALS	34
8	RESULTS OF COLUMN EXOTHERMIC TESTS ON QUEEN'S MATERIALS	35
9	MAXIMUM TEMPERATURE INCREASE IN COLUMN VERSUS HEAT OF REACTION	37
10	CALCIUM CONCENTRATIONS IN BATCH TEST LEACHATES FROM BED MATERIALS	38
11	SULPHATE CONCENTRATIONS IN BATCH TEST LEACHATES FROM BED MATERIALS	39
12	CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831214E BED MATERIAL	41
13	CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 840117E BED MATERIAL	42
14	CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831124D BED MATERIAL	43
15	SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831214E BED MATERIAL	44
16	SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 840117E BED MATERIAL	45
17	SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831124D BED MATERIAL	46

LIST OF TABLES

Table		Page
1	COMPOSITION OF DEVCO AND EVANS COALS	2
2	COMPOSITION OF DRY HAVELOCK LIMESTONE	3
3	OPERATING CONDITIONS AT AFBC UNITS DURING SAMPLING	4
4	MOISTURE CONTENT OF RESIDUES	12
5	RESULTS OF UNCONFINED COMPRESSIVE STRENGTH TESTS	13
6	RESULTS OF PERMEABILITY TESTS ON BED MATERIALS	15
7	WATER HOLDING CAPACITIES	17
8	ELEMENTAL COMPOSITION OF BED MATERIALS	23
9	ELEMENTAL COMPOSITION OF CYCLONE MATERIALS	24
10	ELEMENTAL COMPOSITION OF BAGHOUSE MATERIALS	25
11	ACID NEUTRALIZATION CAPACITY AND pH OF RESIDUES	26
12	RESULTS OF CALORIMETER TESTS	30

1 INTRODUCTION

The atmospheric fluidized bed combustion (AFBC) process is developing as a viable technology for producing energy. It has the ability to burn low grade fuels, handle wide variations in fuel quality, utilize fuel mixtures, reduce NO_x air emissions through relatively low temperature combustion, and control SO_x air emissions from high sulphur coal combustion through reaction with calcined limestone in the combustion zone. The limestone and coarsely crushed coal are fluidized by jets of heated air in a combustion chamber. Temperatures in the combustor are sufficient to calcine the limestone to calcium oxide (unslaked or "quick" lime) which then reacts with liberated coal sulphur to produce calcium sulphate ($CaSO_4$). The calcium sulphate either remains in the combustor and is subsequently removed with other bed material or is captured with other particulate in the stack emission control device. A description of the basic features and advantages of AFBC technology is given in Becker and Code (1982).

In order to achieve efficient sulphur capture, an excess of limestone must be added which results in surplus calcium oxide in the residues. The amount of limestone feed required to maintain adequate sulphur capture increases disproportionately with increasing coal sulphur content. This is reflected in the large amounts of spent bed material produced, and in the substantial amounts of unreacted calcium oxide contained in the wastes.

Due to the increasing interest for use of AFBC in Canada, a series of studies were conducted to evaluate the environmental implications of this new technology. Initial studies indicated that the problems that AFBC wastes might pose during handling and disposal were not well defined (EPS, 1982; CH2M Hill, 1982). This led to the laboratory evaluation of three wastes from a U.S. AFBC test facility, and several sets of wastes from two Canadian AFBC units, the Queen's University Pilot Plant in Kingston, Ontario and the full-scale unit at Canadian Forces Base (CFB) Summerside, Summerside, P.E.I. (EPS, 1985; Constable and Kissel, 1986). The results of these studies showed that wastes from Eastern Canadian high sulphur bituminous coals combusted in limestone beds have unusual properties compared to conventional coal combustion wastes, such as very high solubility, high alkalinity, and exothermic reactivity upon contact with water.

This study was conducted to provide additional information on the properties of wastes generated at the two Canadian AFBC units, and in general to expand the data base on the characteristics of AFBC solid residues. Ten sets of bed, cyclone and baghouse materials from the Queen's pilot plant, and one set of bed and baghouse materials from

the Summerside full-scale unit, were tested and analyzed during this study. Additional tests were also conducted on six sets of the Queen's materials and one set of the Summerside materials that had been partially characterized during the previous study.

The Queen's samples were collected and composited by Queen's pilot plant operating staff after steady state conditions had been achieved in the unit. The solid fuel used during all runs was high sulphur bituminous coal from Evans Coal Mines Limited in Nova Scotia (Table 1). The sulphur sorbent material was Havelock limestone (Table 2). The samples from the Summerside AFBC unit were collected by CANMET and Environment Canada staff during acceptance testing in November, 1983 and demonstration program testing in November, 1984. The solid fuel and sorbent material used during these tests were Devco Prince high sulphur bituminous coal (Table 1) and Havelock limestone.

TABLE 1 COMPOSITION OF DEVCO AND EVANS COALS

	Devco (1)	Evans (2)
Proximate Analysis (%)		
Moisture	0 to 10	1.9 to 2.3
Ash	16 to 22	11.7 to 17.0
Volatile Matter	33.5	34.1 to 35.4
Fixed Carbon	47.2	48.9 to 53.4
Ultimate Analysis (%)		
Carbon	64.2	67.6 to 71.1
Hydrogen	4.0	4.25 to 4.52
Sulphur	5.0 to 6.0	6.36 to 6.81
Nitrogen	1.0	1.14 to 1.24
Ash	16 to 22	11.7 to 12.3
Oxygen (by difference)	6.0	3.59 to 5.6
Ash Analysis (%)		
Silicon	18.6	10.9 to 14.2
Aluminum	13.5	6.5 to 8.8
Iron	18.9	12.4 to 27.6
Titanium	0.7	0.2 to 0.4
Phosphorus	0.3	0.2 to 0.6
Calcium	0.7	3.4 to 12.0
Magnesium	0.3	0.4 to 1.0
Sulphur	0.3	2.3 to 9.4
Sodium	2.0	0.5 to 2.7
Potassium	1.9	1.1 to 1.3

References: (1) Taylor and Friedrich, 1982; (2) Becker et al., 1984

TABLE 2 COMPOSITION OF DRY HAVELOCK LIMESTONE (Taylor and Friedrich, 1982)

	Composition (%)
Loss-on-ignition at 980°C	42.6
Calcium	39.5
Silicon	0.63
Magnesium	0.41
Iron	0.12
Aluminum	0.08
Sulphur	<0.01

All samples were placed into sealed plastic containers immediately after collection to minimize atmospheric contact, and were mixed thoroughly prior to analysis and testing.

The known operating conditions in effect at the Queen's and Summerside units when the samples were collected are summarized in Table 3. The first six sets of Queen's samples and the first set of Summerside samples given in Table 3 were partially characterized in the previous study. The reported conditions include the bed temperature, the percent of excess combustion air (over theoretical stochiometric requirements); the fraction of recycled cyclone dust to the total flow rate of cyclone dust; the molar ratio of calcium equivalent (including calcium and magnesium) in the limestone to the sulphur in the coal fed into the bed; and the diameter of the coal and limestone particles (equivalent to the diameter of the sieve opening that passes 50% by mass of the particles).

TABLE 3 OPERATING CONDITIONS AT AFBC UNITS DURING SAMPLING

Source	Run No.	Bed Temp. (°C)	Excess Air (%)	Cyclone Recycle Fraction	Molar Ca/S Ratio	Particle Diameter (mm)	
						Coal	Limestone
Queen's	831115E	861	-21.1	0.00	4.1	17.0	0.49
	831122E	879	-15.3	0.00	1.7	17.0	0.49
	831124E	863	-19.9	0.55	1.8	17.0	0.49
	831213E	873	-2.3	0.00	3.3	17.0	1.72
	831214E	881	0.0	0.61	3.1	17.0	1.72
	840105E	819	4.1	0.96	3.0	3.0	1.72
	840111E	864	-2.7	0.93	2.6	3.0	1.72
	840117E	862	41.3	0.95	1.3	3.0	1.72
	840124E	827	7.6	0.96	2.9	3.0	0.49
	840126E	873	8.8	0.00	2.7	3.0	0.49
	840207E	872	19.8	0.00	1.6	9.0	0.49
	840215E	921	-5.7	0.63	2.3	9.0	0.49
	840216E	840	12.2	0.00	2.7	9.0	0.49
	840313E	823	13.9	1.00	2.8	17.0	0.49
	840314E	898	1.3	0.00	2.5	17.0	0.49
	840320E	878	29.2	0.00	1.8	17.0	0.49
Summerside	831124D	882	62.2	0.75	2.4	NA	NA
	841104D	NA	NA	0.75	NA	NA	NA

Run No. = Year Month Day; Coal (D = Devco, E = Evans)
NA = Not available

2 EXPERIMENTAL PROGRAM

The physical, chemical, leaching and exothermic properties of the residues were evaluated using a battery of tests and analyses. Most of these tests are similar to those used in the two previous AFBC waste characterization studies. Additional tests, such as unconfined compressive strength, column leaching and bulk density, were conducted during this study to provide information on other characteristics of the wastes.

2.1 Determination of Physical Properties

The physical properties of the residues were examined by conducting tests to determine moisture content, compressive strength, permeability, water holding capacity, bulk density, and moisture/density relationships. Distilled water was used in all tests that required hydration of the residues.

Moisture content was determined in duplicate based on the water loss at 104°C over a 24-hour period (ASTM, 1982; Method D2216-71).

Unconfined compressive strength tests, based on ASTM C109-80, were conducted on 50-mm cubes of bed and baghouse materials. The method is normally used to test the compressive strength of hydraulic cement mortars, and includes specific instructions on how the 50-mm molds are filled in two layers, each layer is tamped 32 times, and the molded samples are stored at 100% humidity. In order to examine how different ash disposal techniques might affect the compressive strength of the residues, four different modifications to the method were used. Two of the modifications dealt with the formation of the 50-mm cubes, and two with storage of the molded samples. For two sets of tests, the molds were filled in three layers with 'as received' residue. Sufficient water to saturate the sample was added after the addition of each layer, and the hydrated material was allowed to stand until all visible expansion had ceased (approximately 5 to 10 minutes) before being tamped according to ASTM C109-80. After all three layers had been added, the samples sat for one hour before the tops were scraped off even with the top of the molds. The samples were left in the molds for 24 hours before removal. One set of these samples was then cured at 100% humidity until tested, and the other set was air dried in a laboratory with no humidity control. These two sets of samples will be referred to as "compacted cured" and "compacted uncured". For the other two sets of tests, the molds were filled in a similar manner except that the material was not tamped. One set of these samples was stored at 100% humidity and the other was air dried with no humidity control. These two sets of samples will be referred to as

"uncompacted cured" and "uncompacted uncured". The molded cubes were tested in a hydraulic compressive testing machine at test ages of 7, 14, 28 and 56 days. The tests were conducted in triplicate on bed materials from Runs 831213E and 840207E, and baghouse materials from Runs 840207E and 840215E.

Falling head permeability tests were conducted on the "as received" bed and baghouse residues (Soiltest, 1978). Samples were hydrated to approximately 20% moisture content and then compacted in a permeameter. Each sample was added to the chamber in 1.5 to 2.0 cm layers to a total depth of approximately 5.5 cm. Each layer was tamped 20 times using the tamping device specified in ASTM C109-80. The coefficient of permeability was calculated from the equation:

$$K = \frac{QL}{A(h_1 - h_0)} \ln (h_0/h_1) \qquad (1)$$

where: K = coefficient of permeability (cm/s)

Q = flow rate during test (mL/s)

L = length of tested residue sample (cm)

A = cross-sectional area of permeameter (cm^2)

h_0 = height of water column at start of test (cm)

h_1 = height of water column at end of test (cm)

The water holding capacity of the materials was determined by placing a known amount of 'as received' residue in a funnel lined with Whatman Number 4 ashless filter paper and covering it with water (Stone and Kahle, 1978). The water was allowed to drain through the sample under the force of gravity until no further drainage occurred for a 5 minute period. In some cases it was necessary to lightly tap the funnel several times during the drainage period in order to obtain reproducible results. The water retained was determined by subtracting the initial dry weight from the wet weight. The water holding capacity of the sample was then calculated as the ratio of the water retained in the sample to the initial dry weight of the sample, expressed as a percentage. In order to investigate if any changes would occur in the water holding capacity of a residue if it was hydrated and dried prior to testing, the procedure was repeated using hydrated residue which had been dried and then crushed using a mortar and pestle.

A variety of bulk density determinations were made on the bed and baghouse materials. Bulk densities were determined for four conditions: 1) loose unhydrated; 2) loose hydrated; 3) compacted unhydrated; and 4) compacted hydrated. The loose

unhydrated bulk density was determined by pouring a sample of residue into a beaker of known volume and determining the weight of the added material. The loose hydrated density was determined in a similar manner, except that the material was wetted with water, dried and then crushed with a mortar and pestle before being added to the beaker. The compacted bulk densities of the bed materials were determined using ASTM D698-70 Method A, in which a rammer is dropped a specific number of times from a certain height to compact the specimens. This procedure could not be used to compact the baghouse materials as the material sprayed out of the mold each time the rammer was dropped. As a result, the baghouse materials were compacted by the same tamping procedure used in forming the unconfined compressive strength cubes.

ASTM D698-70 Method A was also used to determine moisture/density relationships for the "as received" bed and baghouse materials. The same procedure previously described was used, except that the residues were compacted at various moisture contents, and all residues were compacted with a rammer. Since the materials were compacted when they were wet, the problems that were encountered with the baghouse materials during the bulk density tests did not occur during these tests.

No standard test exists to measure the expansion of these types of residues upon hydration. An attempt was made to measure this property by placing 50 g of "as received" material in a glass beaker, uniformly settling the sample level by gently tapping the beaker on the table top, and measuring the volume. An amount of distilled water corresponding to the water holding capacity of the sample was then added to the beaker. The procedure called for the sample volume to be measured after 30 minutes, and an expansion factor to be calculated by dividing the expanded volume by the initial volume. This procedure, however, was abandoned after four trial runs because the beakers broke during each test.

2.2 Determination of Chemical Properties

The chemical characteristics of the residues were evaluated by determining their elemental composition, pH and acid neutralization capacity. The elemental compositions of the residues were determined using inductively coupled argon plasma spectroscopy and flame atomic absorption.

The pH of each residue was determined using ASTM C110-76a. This method involves the mixing by hand of 20 g of sample in 1 L of distilled water. The pH is determined following a one minute period of vigorous mixing and a 20 min. settling period.

The acid neutralization capacity of each residue was determined using ASTM C400-64 method, which involves adding 1.0 g of residue to 20 mL of water, then adding 0.3 N H_2SO_4 (sulphuric acid) until a pH of 4.4 is achieved for an indefinite period of time. As in previous studies, the bed materials were ground in a pulverizing mill to a fine powder prior to testing in order to get a more accurate indication of their total acid neutralization capacities. The cyclone and baghouse materials, because of their much finer particle sizes, were tested as received.

2.3 Determination of Exothermic Properties

The results of the previous studies indicated that the Queen's and Summerside residues, and other AFBC solid residues generated from the combustion of high sulphur content coal in limestone beds, are exothermic when in contact with water. Additional information on this property was collected by repeating the calorimeter and column tests used in the previous studies on the new residue samples.

The calorimeter test (ASTM C110-76a) was used to determine the heat of reaction (loss of enthalpy) per unit mass of the residues. A known mass of sample was added in a single motion to 600 mL of distilled water contained in a 1-L Dewar flask (calorimeter), and the temperature of the well stirred mixture monitored until a temperature peak was observed. Each residue was hydrated at liquid-to-solid ratios of 3:1, 5:1 and 10:1.

The column exothermic test was used to examine temperature variations at various depths of residue, and to examine exothermic reactions of larger masses of residue under different slaking conditions than those used in the calorimeter test (i.e., to give some indication of what might happen in a field disposal situation where a layer of dry material was exposed to rain). Additional information on the permeability and leachability of the residues was also gained from the tests. The column was first used in the 1982/83 study, and underwent several modifications because of problems caused by violent thermal reactions and high temperatures. The final 1982/83 design consisted of an 8-cm diameter stainless steel column (40 cm in height) which was lined with a teflon sleeve and was fitted with five dial thermometers. The thermometers were positioned at 4-cm intervals throughout the column, with the top thermocouple located about 4 cm below the residue surface. The column was wrapped in fibreglass insulation and held vertically in a retort stand. The top of the column was filled with a layer of glass beads in order to help distribute the flow of water evenly over the surface of the material. Distilled water was added to the top of the column at a rate of 1.24 mL/min, to simulate

a precipitation rate of 1.6 cm/h. Monitoring continued until approximately 30 to 60 minutes after detection of a peak in the bottom thermocouple.

The column test apparatus was again modified during the 1983/84 study. The only planned design change was the replacement of the dial thermometers with thermocouples which were interfaced to a computer. The temperatures at the thermocouples were recorded in a computer data file at 2 to 5 minute intervals. However, several other modifications became necessary during the study because of pressures created inside the column when the residues were hydrated. The pressure bent the thermocouples and the wire screen on the bottom of the column downward as much as 1 cm during some initial runs. The thermocouples had to be modified three times with successively stronger outer sheathing before they were able to survive a test without excessive deformation. The final design used 0.9-mm thick 316 stainless steel formed into a 6-mm outer diameter tube which enclosed each thermocouple. The wire screen at the base of the column was also replaced with a circular 1.6-mm thick stainless steel plate drilled on 6.4-mm centres with 3.2-mm holes.

No further problems with excessive deformation of the thermocouples and base plate were encountered after these changes were made. The delay caused by the modifications, however, limited the number of column exothermic tests that could be made during this study. The samples that were selected for testing were the bed and baghouse materials from the two Summerside runs and from Queen's Runs 831214E and 840117E. Since the previous study had shown a strong correlation between calcium content and the heat of reaction of the residues, the Queen's samples were selected because of their relatively high and low calcium contents. More Run 831214E baghouse material was used in the other tests than was originally anticipated; therefore, the column exothermic test with this material could not be done. The Summerside samples were selected because they were collected from a full-scale system, and because they allowed comparisons to be made between two combustors using similar coals and the same limestone.

2.4 Determination of Leaching Properties

The leachability of the residues was examined using both the serial batch leaching tests that had been employed in the previous studies, and column leaching tests. Serial batch leaching tests had been used previously because they require only a fraction of the time needed to conduct column leaching test (e.g., 20 days versus several months). The column tests were added to this study to generate leaching results under conditions

which were more representative of a field disposal situation, and to allow comparisons with the batch leaching results.

The serial batch leaching tests were conducted by leaching each residue for 20 cycles with distilled water at a 20:1 liquid-to-solid ratio. After each 18 hour cycle of mixing in a square polyethythene bottle, the suspended solids were separated from the leachate by centrifugation and decantation, followed by filtration through 0.45-μm membrane filter paper. The leachate was retained for analysis, and the solids contacted with fresh distilled water for the next leaching cycle. The pH, conductivity, total dissolved solids, calcium, chloride and sulphate concentrations of the leachates were determined for every cycle. Leachates from Cycles 1, 2, 5, 10 and 20 were also analyzed for other elements. Calcium, chloride and sulphate were selected for analysis every cycle because they were the major constituents of the leachates in the previous study.

The column leaching tests were conducted by packing each residue into a column, adding distilled water at a constant rate to the top of the column, and collecting the leachate from the bottom of the column. Each column consisted of a 50-mm inner diameter acrylic cylinder (26 cm in length) fitted with a rubber stopper base containing a drain plug and plastic tubing. The bottom of the column was packed with approximately 3 cm of glass wool, and residue was then added and tamped in several layers to a depth of 16 to 18 cm. The residues were hydrated, dried and crushed with a mortar and pestle prior to placement in the columns. The top of the column was then filled with a layer of glass beads to distribute the added water evenly over the surface of the residue. The column was topped with a loose fitting rubber stopper containing plastic tubing.

The initial pore volume of each column was determined by adding distilled water to the column until the residue was completely saturated. These values were then used to determine the frequency of leachate analysis and to allow the results of the column and batch leaching tests to be compared on a liquid-to-solid ratio basis.

Using a peristaltic pump, distilled water was added to the top of the columns at the rate of 0.03 mL/min which is equivalent to a precipitation rate of 0.09 cm/h. This rate was based on the average annual precipitation at Summerside, P.E.I. of approximately 1000 cm (0.11 cm/h). This rate of water addition is much less than that of 1.6 cm/h used in the column exothermic tests. The latter value was selected to simulate conditions during a rain storm. The rate used in the column leaching tests is based on the average annual precipitation as the tests were conducted to examine leaching characteristics over several months.

Leachates were composited every 2 to 3 pore volumes until approximately 15 pore volumes of leachate had been generated, then composited every 6 pore volumes. The composited samples were filtered through 0.45-μm filter paper prior to analysis for the same parameters measured in the batch leaching tests.

The column leaching tests were performed in duplicate on the same Queen's samples subjected to the column exothermic tests (i.e., Runs 831214E and 840117E) and on the bed and baghouse materials from Summerside Run 831124D. However, the baghouse material tests had to be discontinued as all flow through these columns ceased after only 2 to 3 pore volumes of leachate has been collected. They were replaced with 1:1 mixtures of bed and baghouse materials, but these columns also ceased leachate production after only a few pore volumes.

It was originally planned to perform the batch leaching tests in duplicate on these same six materials; however, only a few of these tests were done because of time and budget constraints. The tests were performed on the bed and baghouse materials and a 1:1 mixture of these materials from Run 831214E, and on the bed material from Run 840117E.

3 RESULTS AND DISCUSSION

3.1 Physical Properties

3.1.1 Moisture Content. The results of the moisture content analyses are given in Table 4. Moisture contents were measured to determined if residues had absorbed any moisture from the atmosphere during storage and handling prior to exothermic testing. The moisture content was 0.00% in all bed materials, ranged between 0.00% and 0.02% in the cyclone materials and was less than 1.0% in the baghouse materials except those from Runs 840207E, 840313E and 840320E. The reason for the higher moisture contents of these samples is not known. Problems were encountered with moisture content determinations for all of the bed materials and most of the cyclone materials, as they became hygroscopic (i.e., absorbed moisture) when heated. This same problem was found with the bed materials in the previous study, but not with the cyclone materials.

TABLE 4 MOISTURE CONTENT OF RESIDUES (%)

Source	Run No.	Bed Material	Cyclone Material	Baghouse Material
Queen's	840111E	0.00*	0.01	0.29
	840117E	0.00*	0.00*	0.98
	840124E	0.00*	0.00*	0.41
	840126E	0.00*	0.00*	0.48
	840207E	0.00*	0.00*	1.39
	840215E	0.00*	0.02	0.54
	840216E	0.00*	0.00*	0.70
	840313E	0.00*	NA	0.54
	840314E	0.00*	0.00*	1.87
	840320E	0.00*	0.00*	4.03
Summerside	841104D	0.00*	NA	0.00*

* Hygroscopic NA = Not available

3.1.2 Compressive Strength. The results of the unconfined compressive strength tests are given in Table 5. Most cubes that were formed without tamping disintegrated when they were removed from the molds, with the exception of those made from

TABLE 5 RESULTS OF UNCONFINED COMPRESSIVE STRENGTH TESTS

Test Conditions	Number of Days	Bed Material Run No. 831213E Pressure (kPa) 1	2	3	Avg.	Bed Material Run No. 840207E Pressure (kPa) 1	2	3	Avg.	Baghouse Material Run No. 840207E Pressure (kPa) 1	2	3	Avg.	Baghouse Material Run No. 840215E (Pressure (kPa) 1	2	3	Avg.
Uncompacted, Uncured	7	Cubes disintegrated when removed from molds.				914	937	907	919	Cubes disintegrated when removed from molds.				Cubes disintegrated when removed from molds.			
	14					1420	1450	1120	1330								
	28					D	1430	1200	1320								
	56					1290	1440	1240	1320								
Uncompacted, Cured	7	Cubes disintegrated when removed from molds.				682	704	592	659	Cubes disintegrated when removed from molds.				Cubes disintegrated when removed from molds.			
	14					749	644	794	729								
	28					1230	1090	1330	1220								
	56					1030	1530	1930	1500								
Compacted, Uncured	7	1560	D	2100	1830	2130	2800	D	2470	734	674	539	649	2660	2020	1710	2130
	14	989	869	1390	1080	2130	2400	2170	2230	405	1110	989	835	3190	2660	3710	3190
	28	1210	1830	974	1340	1870	1270	D	1570	300	465	2010	925	2950	3420	2210	2860
	56	1250	1430	D	1340	D	2790	2240	2520	510	480	D	495	1790	2720	1540	2010
Compacted, Cured	7	375	390	442	402	1350	1330	1170	1280	1140	794	1090	1010	2730	3040	2660	2810
	14	689	682	787	719	1210	1140	1290	1220	764	1140	2410	1440	4300	3730	4370	4130
	28	1050	D	914	982	2100	2430	2670	2400	802	2320	1000	1320	3040	3930	4110	3690
	56	1240	1050	1370	1220	4370	4220	4560	4380	644	974	1600	1070	2660	2090	2170	2310

D = Damaged cube, not tested

Run 840207E bed material. The strength of these uncompacted cubes was two to three times less than the strength of the compacted cubes made from this material. Some of the compacted cubes had partially disintegrated when it came time to test them (see Table 5).

Widely varying results were obtained from some of the triplicate sets of cubes that were formed and stored under the same conditions. For example, the 28 day compressive strengths of the compacted uncured baghouse material cubes from Run 840207E varied from 300 to 2010 kPa. On the other hand, the reproducibility of the test results on some of the materials, such as the compacted cured bed material from Run 840207E and the compacted cured baghouse material from Run 840215E, was very good. Because of the wide variability in the strengths of some of the triplicate sets of cubes, it is difficult to interpret the results. In general, it appears that the maximum strength of the compacted bed material cubes decreased with time when the cubes were uncured but increased when the cubes were cured. The maximum strength of both the cured and uncured compacted baghouse material cubes peaked after two to four weeks then decreased.

3.1.3 Permeability. The results of the falling head permeability tests conducted on the bed materials are shown in Table 6. The average coefficients of permeability in the Queen's bed materials varied by three orders of magnitude, and ranged between 8.79×10^{-5} and 1.63×10^{-2} cm/s. The average coefficients of permeability of the two Summerside bed materials were 3.20×10^{-3} and 4.03×10^{-3} cm/s, and were of the same order of magnitude as the majority of the coefficients measured in the Queen's bed materials. The coefficients at the upper limit of the range (10^{-2} cm/s) are typical of clean medium sands, and values at the lower limit of the range (10^{-5} cm/s) are typical of silty sands and sandy clays. For comparison, Stone and Kahle (1978) reported coefficients for AFBC spent bed materials in the range of 6.8×10^{-4} to 3.7×10^{-2} cm/s, and a value of 2.4×10^{-2} cm/s was measured in two bed materials in the 1982/83 study.

The permeability tests were performed in duplicate or triplicate on each material, and several measurements were made during each test, so that each average is based on 9 to 19 permeability measurements. Reproducibility of these measurements was usually very good, as indicated by the relatively small standard deviations shown in Table 6. The "within test" standard deviation was usually one to two orders of magnitude less than the "between tests" standard deviation, indicating that the variability of successive permeability measurements within each test was usually much smaller than the

TABLE 6 RESULTS OF PERMEABILITY TESTS ON BED MATERIALS

Source	Run No.	Average Coefficient of Permeability (cm/s)	Standard Deviations (cm/s)	
			Within Each Test	Between Tests
Queen's	840111E	6.48E-04	8.99E-06	1.98E-04
	840117E	8.79E-05	6.93E-07	1.17E-05
	840124E	1.59E-02	7.96E-05	7.07E-04
	840126E	7.97E-03	2.07E-04	3.98E-04
	840207E	1.63E-02	2.55E-04	1.41E-04
	840215E	1.18E-03	1.66E-05	3.82E-04
	840216E	7.57E-03	1.84E-04	6.65E-04
	840313E	3.64E-03	4.86E-05	3.91E-04
	840314E	1.63E-03	1.87E-05	2.12E-04
	840320E	4.59E-03	2.05E-04	1.54E-03
Summerside	831124D	3.20E-03	7.68E-05	1.63E-03
	841104D	4.03E-03	2.85E-04	1.32E-03

variability of permeability measurements made on different samples of the same material. In most cases, the variability of successive permeability measurements within a test was random; however, this was not true for all samples. For example, the coefficients of permeability continually decreased during successive trials on the same bed materials samples from Runs 840126E and 840216E, whereas they continuously increased during successive trials on the same bed material samples from Runs 840320E and 841104D. The reasons for these opposing trends are not known.

Between test variability was probably largely due to the lack of a specified compaction force in the procedure. This resulted in different densities in replicated tests on the same bed material, which influenced the permeability of each sample (i.e., permeability decreased as density increased). It is recommended that future permeability tests be conducted using a reproducible compaction procedure, such as the one given in ASTM D698-70 which uses a rammer dropped a set number of times from a specified height to compact specimens.

Attempts were made to measure the permeabilities of the baghouse materials using the falling head permeability test. During initial trials, however, the baghouse

materials separated into layers inside the sample chamber. The materials were then tightly compacted which solved the layering problem, but resulted in permeabilities which were too low to be measured accurately on a falling head permeameter. The low permeability of the baghouse materials was confirmed during the column leaching tests. Only 2 to 3 pore volumes of leachate were collected from the baghouse material columns before all water flow through the columns ceased.

3.1.4 **Water Holding Capacity.** The results of the water holding capacity tests are given in Table 7. Water holding capacities were measured to give some indication of the amount of water that a landfilled waste might retain against the force of gravity before it began to release leachate. The tests were conducted on "as received" samples and on hydrated, dried and crushed samples to determine if any changes would occur in the water holding capacity of a residue if it was hydrated, dried and crushed prior to disposal in a landfill.

The average water holding capacities of the 'as received' Queen's residues ranged from 37% in the bed materials to 67% in the cyclone materials to 82% in the baghouse materials. This same pattern of lowest capacities in the bed materials and highest in the baghouse materials was found in the previous studies, and is likely due to the decreasing particle sizes of the residues progressing from bed material to cyclone material to baghouse material. The water holding capacities of the Summerside residues from Run 841104D were within the ranges measured in the corresponding Queen's residues. All water holding capacity results are comparable to those measured in the previous study. As found in the previous study, some of the materials swelled considerably when wetted; therefore, the results of the water holding capacity tests may not be directly comparable. However, the problem that occurred in the previous study with the wetting of two Queen's baghouse materials (the materials did not become wet when water was added but floated on the surface of the water) did not occur during this study.

As shown in the last 3 columns of Table 7, hydrating, drying and crushing the samples prior to water capacity determinations increased the capacities of the bed materials by an average of 44%, but had no consistent effect on the capacities of the cyclone and baghouse materials. The increase in the bed material capacities may have been caused by crushing and/or by the bed material particles swelling when they are hydrated. These actions would have increased particulate surface area, resulting in a greater capacity to retain water against the force of gravity.

TABLE 7 WATER HOLDING CAPACITIES (%)

Source	Run No.	As Received			Hydrated and Dried Prior to Testing			Ratio of Hydrated to As Received		
		Bed	Cyclone	Baghouse	Bed	Cyclone	Baghouse	Bed	Cyclone	Baghouse
Queen's	840111E	46.6	55.0	83.0	59.3	71.5	96.4	1.27	1.30	1.16
	840117E	50.1	72.1	89.5	56.1	62.7	76.3	1.12	0.87	0.85
	840124E	35.3	54.5	76.0	49.3	68.7	89.6	1.40	1.26	1.18
	840126E	35.9	77.9	90.6	53.4	74.5	94.7	1.49	0.96	1.05
	840207E	28.7	69.3	92.5	48.5	62.7	75.9	1.69	0.90	0.82
	840215E	45.8	60.6	85.6	73.7	63.5	82.7	1.61	1.05	0.97
	840216E	34.2	71.5	84.5	47.5	59.6	90.8	1.39	0.83	1.07
	840313E	28.9	NA	71.1	42.5	NA	83.6	1.47	NA	1.18
	840314E	33.3	63.0	80.7	52.3	70.9	78.5	1.57	1.13	0.97
	840320E	31.8	77.3	70.2	43.6	71.6	61.6	1.37	0.93	0.88
	Mean	37.1	66.8	82.4	52.6	67.3	83.0	1.44	1.03	1.01
Summerside	841104D	43.2	NA	74.2	63.1	NA	88.4	1.46	NA	1.19

each entry is an average of 2 measurements
NA = Not available

3.1.5 Bulk Density. The results of the bulk density determinations on the bed and baghouse materials are shown in Figures 1 and 2. Loose dry densities ranged from 1.14 to 1.45 g/cm^3 in the Queen's bed materials, and from 0.47 to 0.60 g/cm^3 in the Queen's baghouse materials. The loose dry density of the unhydrated Summerside bed material, at 1.40 g/cm^3, was within the range measured in the Queen's bed materials. The loose dry density of the unhydrated Summerside baghouse material, at 0.82 g/cm^3, was considerably higher than any of the Queen's baghouse densities. By comparison, Stone and Kahle (1978) reported loose dry densities from four AFBC units ranging from 0.73 to 1.36 g/cm^3 for the spent bed materials and from 0.74 to 1.46 g/cm^3 for the fly ashes. Compaction increased the densities of the Queen's bed and baghouse materials by averages of 18% and 43%, respectively, and of the Summerside bed and baghouse materials by 10% and 11%, respectively.

Hydration decreased the dry densities of the Queen's bed materials by an average of 27% and of the Summerside bed and baghouse materials by 31% and 13%, respectively, but increased the densities of the Queen's baghouse materials by an average of 19%. By comparison, Stone and Kahle (1978) reported changes in dry densities after hydration ranging from a decrease of 51% to an increase of 48% for the bed materials, and from no change to a decrease of 40% in the fly ashes.

Compacting the hydrated residues resulted in bed material densities that were approximately the same as the "as received" loose densities, and increased the density of the hydrated Queen's baghouse materials by an average of 25% and of the hydrated Summerside baghouse material by 12%. In order to decrease landfill volume requirements, these results indicate that the residues should be hydrated and compacted prior to final disposal in a landfill.

3.1.6 Expansion During Hydration. Four trial expansion tests were attempted using four different Queen's bed materials. During each test, the material expanded with sufficient pressure to break the beaker. Consideration was given to repeating the test in a steel or plastic beaker which would not break, but this procedure was not tried since the usefulness of a test where the material is only allowed to expand in one direction is questionable. Consideration was then given to using an expandable rubber bag, but this procedure was not tried since exothermic reactions in the residues would have melted the bag. Problems caused by residue expansion were also encountered during the column leaching tests and the column exothermic tests.

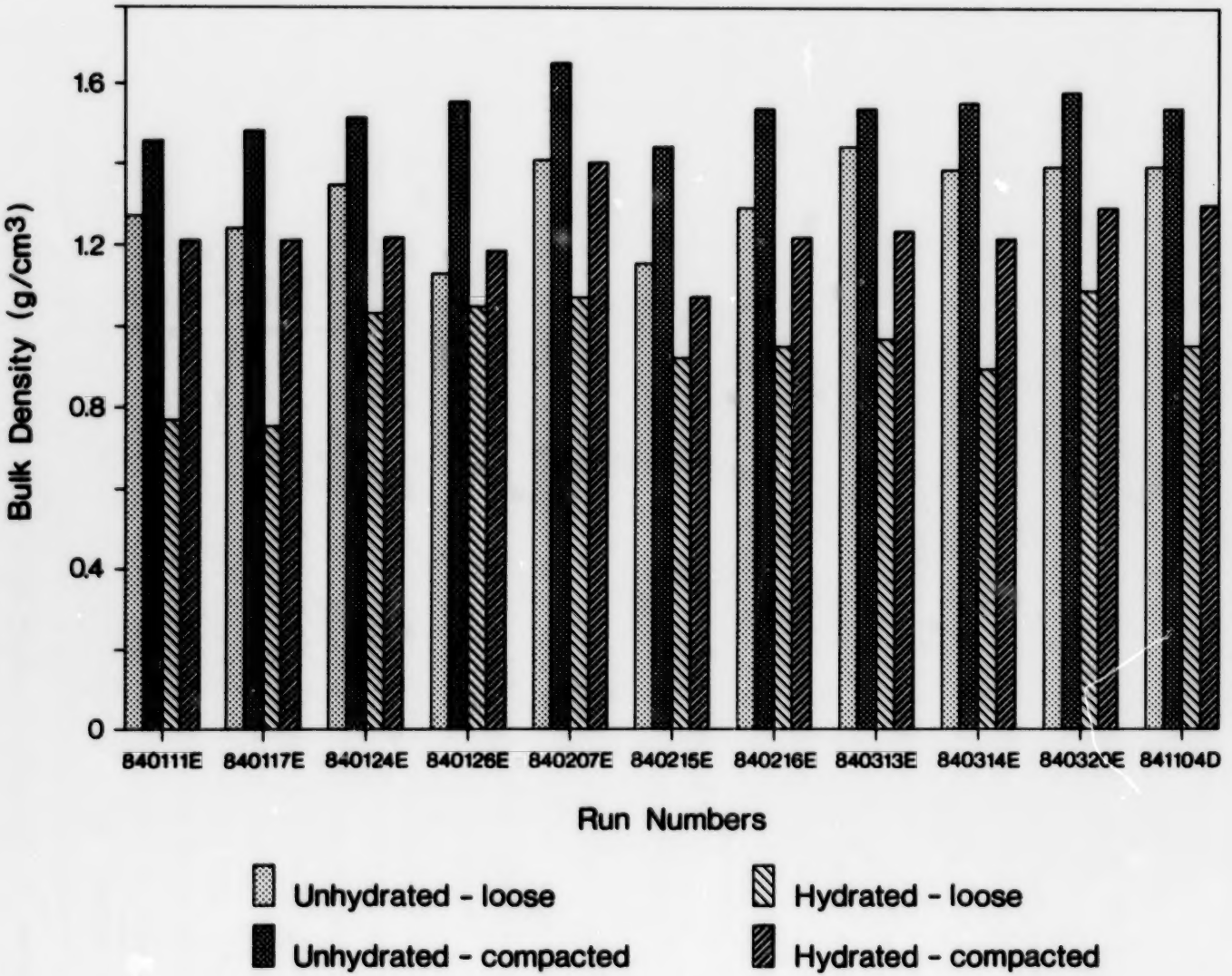

FIGURE 1 BULK DENSITIES OF BED MATERIALS

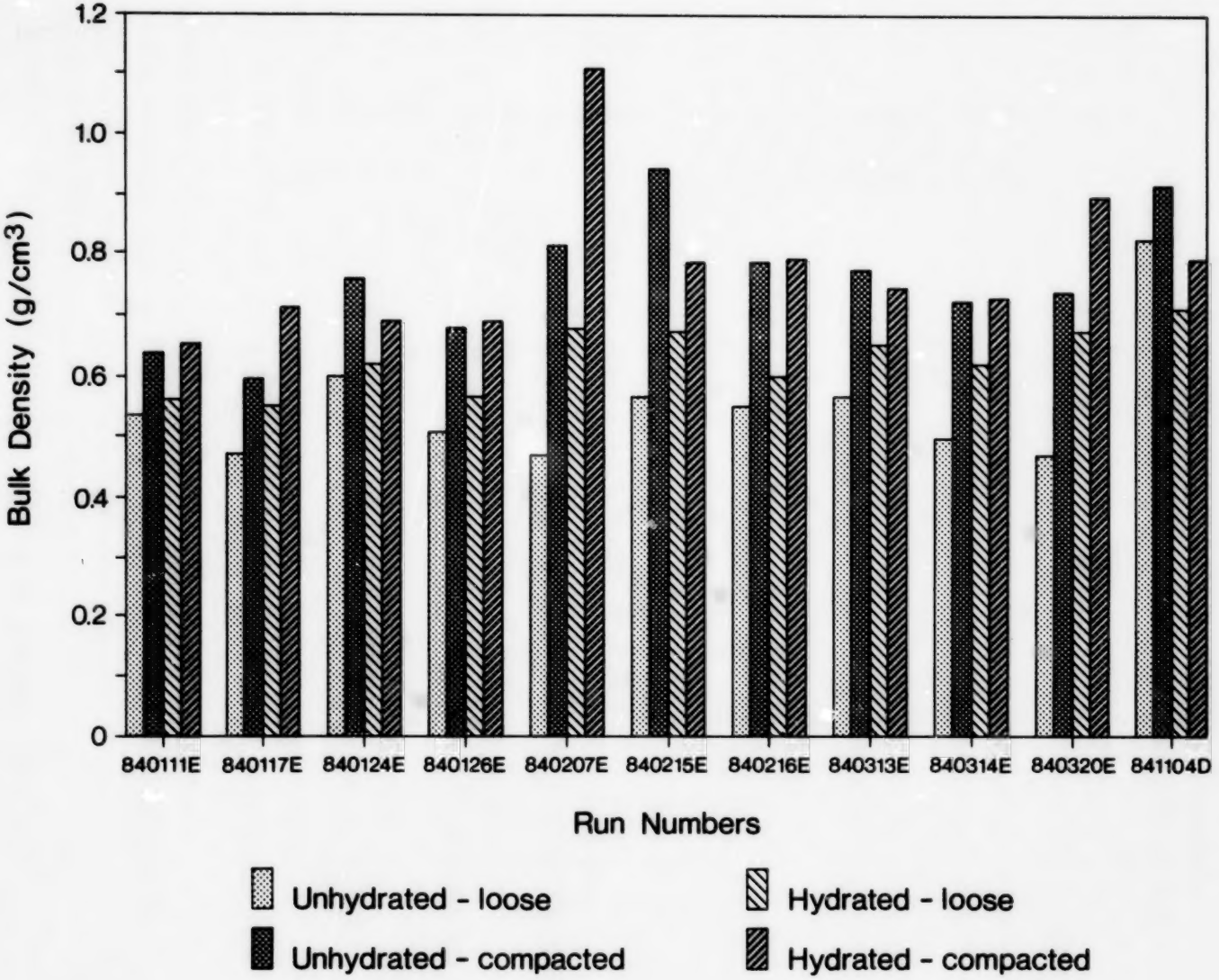

FIGURE 2 BULK DENSITIES OF BAGHOUSE MATERIALS

3.1.7 Moisture/Density Relationships. The results of the moisture/density tests are given in Figure 3. Shown are the typical shapes of the bed and baghouse material response curves observed during the tests, and the maximum densities achieved for each residue. The maximum density to which a material can be compacted is important in landfill disposal design since the volume of material to be disposed decreases as waste density increases. Optimum densities for the bed materials ranged from 1.38 to 1.56 g/cm^3 at moisture contents ranging between 14.9% and 25.9%. These results are comparable to those of Integ (1979), who reported a maximum density of 1.45 g/cm^3 at a moisture content of approximately 30% for an AFBC spent bed material generated from a British coal and limestone. Optimum densities for the baghouse materials ranged from 1.04 to 1.26 g/cm^3 at moisture contents ranging between 37.7% and 48.6%.

These results and those of the water holding capacity, permeability and bulk density tests suggest that the residues should be hydrated, dried (if necessary) to between 20% and 50% moisture, and compacted (e.g., by earthmoving equipment) prior to final disposal in a landfill. This would delay the commencement of leachate release from the landfill, decrease disposal volume requirements, and decrease the permeability of the residues (i.e., decrease the leachate production rate).

3.2 Chemical Properties

3.2.1 Residue Composition. The elemental compositions of the residues are given in Tables 8 to 10. Major elements are expressed in percent weight whereas minor elements are expressed in µg/g. The residues were composed primarily of calcium, sulphur, silicon, iron and aluminum. The results are comparable to those from the previous study.

3.2.2 Acid Neutralization Capacity. The acid neutralization capacities of the residues are reported in Table 11. The values for the Queen's residues ranged from 11.0 to 18.1 g-equiv./kg for the bed materials, 4.68 to 14.5 g-equiv./kg for the cyclone materials, and 0.93 to 5.61 g-equiv./kg for the baghouse materials. These values are comparable to those obtained in the previous study, except for the low capacities of some of the cyclone and baghouse materials, particularly those from Runs 840117E and 840320E. The value for the Summerside bed material, at 12.9 g-equiv./kg, was within the range measured in the Queen's bed materials and comparable to the value of 14.5 g-equiv./kg measured in the Summerside bed material sample in the previous study. The capacity of the Summerside baghouse material, at 3.40 g-equiv./kg, was within the range measured in the Queen's baghouse materials, but was less than the value of 12.1 g-equiv./kg measured in the Summerside baghouse material sample in the previous study.

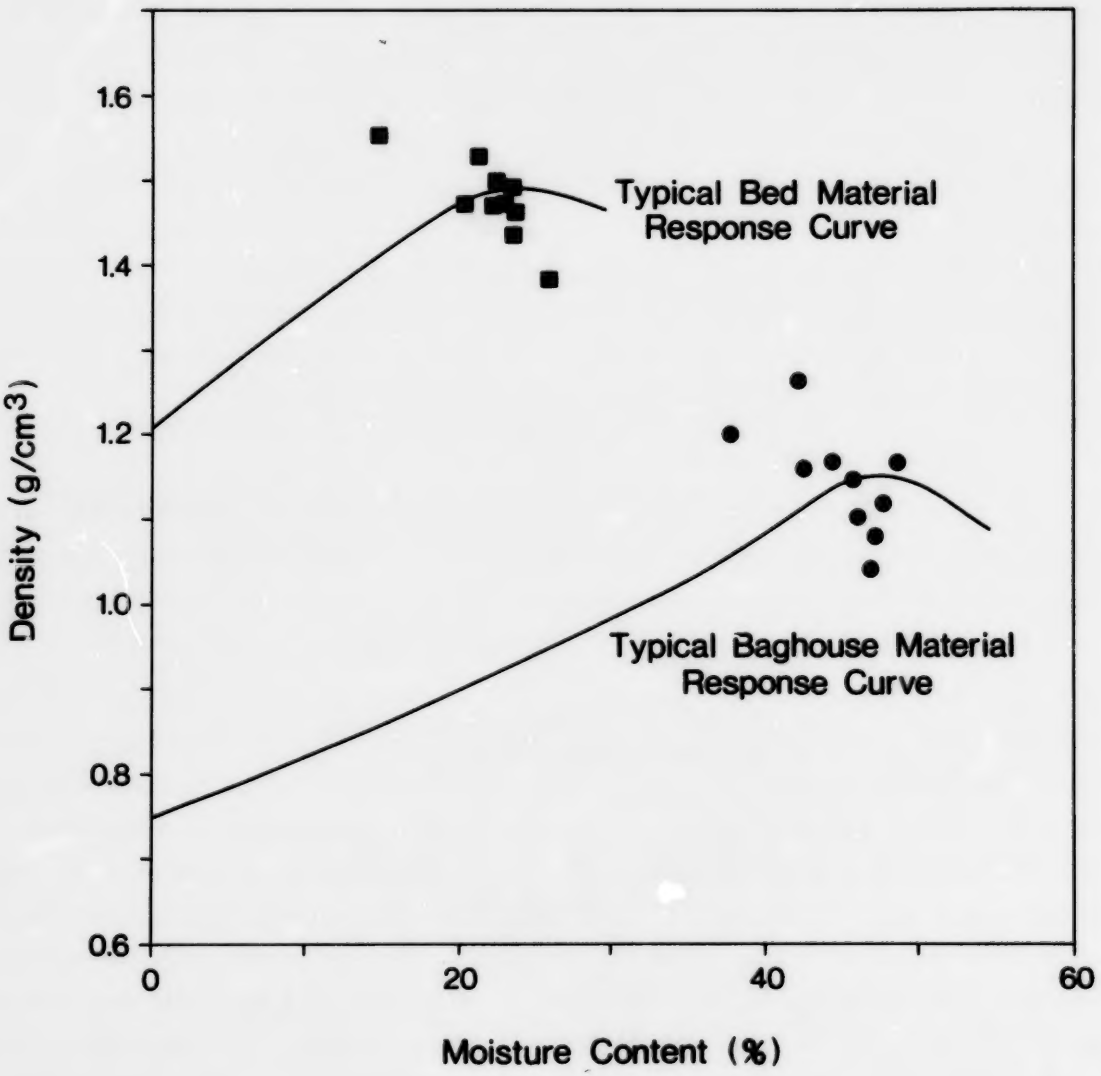

FIGURE 3 RESULTS OF MOISTURE/DENSITY TESTS

TABLE 8 ELEMENTAL COMPOSITION OF BED MATERIALS

	Queen's										Summerside
Parameter	840111E	840117E	840124E	840126E	840207E	840215E	840216E	840313E	840314E	840320E	841104D
Major Elements (%)											
Al	1.40	2.90	1.40	1.60	1.10	1.10	0.90	0.60	0.60	0.90	1.80
Ca	38.0	34.5	40.0	40.0	36.0	42.0	36.0	41.0	40.0	36.0	35.7
Fe	2.00	3.30	1.60	1.70	3.30	2.70	2.10	2.10	2.10	2.50	1.39
K	0.38	0.62	0.30	0.31	0.16	0.14	0.11	0.06	0.05	0.10	0.22
Si	2.60	5.10	2.70	2.90	2.10	2.10	1.70	1.40	1.30	2.00	3.20
TS	12.1	9.8	14.3	14.6	17.0	7.32	15.6	12.4	15.2	17.0	12.5
Minor Elements (ppm)											
As	25.0	46.0	27.0	34.0	52.0	20.0	22.0	22.0	32.0	26.0	23.0
Ba	500	1031	725	758	701	1110	743	632	631	1088	193
Cu	176	42.0	113	88.0	39.0	58.0	30.0	26.0	34.0	48.0	34.3
Pb	< 4.0	63.5	47.0	44.0	5.50	38.0	13.0	< 4.3	< 6.8	< 6.0	29.5
Mg	3260	5782	4145	3986	3119	4637	3883	1806	3713	4158	3593
Mn	441	546	494	307	347	806	542	271	571	630	385
Ni	970	31.0	362	321	50.0	163	43.0	52.0	88.0	78.0	61.0
P	263	288	275	325	350	313	300	313	338	363	740
Na	1050	2124	990	1085	1092	793	810	496	434	660	322
Sr	66.0	172	188	141	140	244	295	110	211	294	11.0
Ti	2448	4414	2751	2814	2677	2614	2262	2187	2053	2747	740
V	36.0	61.5	54.0	45.0	46.0	53.0	52.0	36.0	54.0	66.0	34.0
Zn	441	1019	395	307	347	202	271	181	143	252	135.0

TABLE 9 ELEMENTAL COMPOSITION OF CYCLONE MATERIALS

Parameter	Queen's 840111E	840117E	840124E	840126E	840207E	840215E	840216E	840313E	840314E	840320E
Major Elements (%)										
Al	2.30	5.10	1.70	2.20	1.80	2.00	1.40	NA	1.50	2.70
Ca	31.0	11.4	38.0	37.0	27.0	33.0	34.0	NA	38.0	19.0
Fe	7.30	17.0	5.50	8.00	11.0	9.50	7.20	NA	8.70	15.0
K	0.45	0.93	0.33	0.44	0.27	0.33	0.26	NA	0.23	0.38
Si	4.50	9.20	3.50	4.10	3.90	4.30	3.30	NA	3.40	5.80
TS	9.22	5.59	9.22	6.16	7.17	6.22	6.99	NA	6.64	6.50
Minor Elements (ppm)										
As	< 5	26.0	17.0	32.0	30.0	36.0	< 5	NA	25.0	9.00
Ba	1202	2307	1185	1467	1548	2011	1345	NA	1759	3010
Cu	38.0	60.0	29.0	40.0	46.0	54.0	28.0	NA	41.0	59.0
Pb	54.0	210	110	60.0	112	45.0	45.0	NA	49.0	257
Mg	6804	NA	3833	4080	2249	2363	1529	NA	1894	3049
Mn	680	683	613	563	428	567	470	NA	431	554
Ni	32.0	70.0	22.0	13.0	51.0	27.0	34.0	NA	25.0	33.0
P	363	650	375	375	538	538	388	NA	438	738
Na	2220	4136	1800	2100	2646	2430	1860	NA	2318	3718
Sr	207	75.0	106	196	165	142	81.0	NA	276	252
Ti	4048	6662	2976	3832	3117	4456	2773	NA	3103	4481
V	81.0	185	48.0	89.0	89.0	105.0	73.0	NA	56.0	124
Zn	1588	2923	1472	2758	1178	1229	1058	NA	947	1663

NA = Not available

TABLE 10 ELEMENTAL COMPOSITION OF BAGHOUSE SAMPLES

	Queen's										Summerside
Parameter	840111E	840117E	840124E	840126E	840207E	840215E	840216E	840313E	840314E	840320E	841104D
Major Elements (%)											
Al	4.20	5.40	3.30	4.90	5.40	4.70	4.80	3.20	3.70	5.00	4.00
Ca	21.0	7.20	17.0	14.0	9.00	12.0	13.0	19.0	14.0	10.0	10.80
Fe	15.0	18.0	15.0	19.0	21.0	21.0	20.0	17.0	16.0	21.0	18.0
K	0.69	0.82	0.53	0.78	0.80	0.71	0.74	0.50	0.68	0.80	0.67
Si	5.80	7.20	4.80	6.80	7.00	6.20	6.20	4.90	5.10	6.60	7.10
TS	7.10	6.89	5.35	4.89	4.71	5.59	5.79	5.89	5.93	5.32	2.93
Minor Elements (ppm)											
As	27	80	73	36	112	117	150	50.0	82.0	76.0	22.0
Ba	3518	3831	1930	3151	4009	3499	4509	2706	3153	4007	297
Cu	107	122	82	127	177	138	137	101	140	148	86.5
Pb	643	714	286	720	1317	685	617	269	525	1071	51.0
Mg	3213	NA	158	603	74	311	2778	834	830	2785	2064
Mn	428	347	321	309	359	428	412	353	315	321	280
Ni	56	99	61	74	131	92.0	98.0	56.0	90.0	102	42.0
P	750	900	550	763	1150	1125	1175	863	1138	1485	NA
Na	5246	6611	4061	7560	9720	8280	9052	5733	6820	9720	1300
Sr	260	193	70	221	236	138	452	103	327	338	13
Ti	9060	11431	5268	8939	11628	9003	9159	5602	6976	9695	3295
V	221	505	244	393	673	564	482	304	226	434	122
Zn	4391	5273	2678	3293	3232	2570	2161	1999	2415	2463	149

NA = Not available

TABLE 11 ACID NEUTRALIZATION CAPACITY AND pH OF RESIDUES

Source	Run No.	Acid Neutralization Capacity*			pH		
		Bed	Cyclone	Baghouse	Bed	Cyclone	Baghouse
Queen's	840111E	16.3	12.4	5.41	12.2	12.5	12.4
	840117E	14.3	4.68	0.93	12.3	11.9	11.1
	840124E	13.8	14.3	5.30	12.0	12.4	12.5
	840126E	13.8	14.5	3.38	12.1	12.3	12.3
	840207E	11.0	11.3	1.61	12.1	12.3	11.4
	840215E	18.1	14.4	2.90	12.2	12.4	12.3
	840216E	13.0	14.4	2.83	12.1	12.3	12.1
	840313E	13.5	NA	5.61	11.9	NA	12.4
	840314E	14.1	14.3	3.85	12.0	12.5	12.0
	840320E	11.9	6.69	1.36	12.2	11.9	11.1
	Mean	14.0	11.9	3.32	12.1	12.3	12.0
Summerside	841104D	12.9	NA	3.40	12.0	NA	11.5

* gram-equivalent/kg
NA = Not available

The acid neutralization capacity of a residue represents its ability to resist a decrease in pH. As found in the previous study, the high acid neutralization capacities of the bed and cyclone materials indicate that leachates from these wastes will remain highly alkaline until a considerable amount of leaching has occurred. This was verified by the results of the leaching tests (Section 3.4).

Linear regression analyses conducted in the previous study indicated significant relationships existed between the acid neutralization capacity of the three materials and their calcium and calcium oxide content, and between the acid neutralization capacity of the bed material and its total sulphur content. These analyses (except for calcium oxide content) were repeated using all the data from this and the previous study. The results are shown in Figures 4 and 5. A significant linear correlation was found between acid neutralization capacity and calcium content. The correlation coefficient for the regression line shown in Figure 4 is 0.93. The increase in acid neutralization capacity with increasing calcium content is expected since calcium is an

alkaline earth metal. The graph of acid neutralization capacity versus sulphur content (Figure 5) indicates that the results are grouped into two distinct regions. The acid neutralization capacities of residues with sulphur contents less than 6% were much less than those with sulphur contents greater than 8%. Within each region, however, there was no significant correlation between the two variables.

3.2.3 pH. The results of the pH determinations on the solid residues are given in Table 11. The pH of all residues was between 11.1 and 12.5, indicating the residues are very alkaline. These results are similar to those of 12.0 to 12.7 measured in the previous study. As expected, leachates produced by water contact with these wastes were also highly alkaline (Section 3.4).

3.3 Exothermic Properties

The exothermic properties of the residues were investigated through use of calorimeter tests to determine heats of reaction, and of column tests to examine temporal variations in temperature at various depths of residue within the column.

3.3.1 Calorimeter Tests. The results of the calorimeter tests are given in Table 12. The heat of reaction or loss of enthalpy per unit mass of residue ($-\Delta H$) was determined from the equation:

$$-\Delta H = \frac{W(T_{max} - T_0)}{m} \qquad (2)$$

where: W = the "equivalent in water" of the calorimeter (2.74 kJ/K)

T_0 = the initial temperature (K)

T_{max} = the maximum temperature (K)

m = mass of sample (kg)

$-\Delta H$ is expressed in kJ/kg

The average heats of reaction of the Queen's and Summerside residues ranged from 251 to 422 kJ/kg for the bed materials; 93 to 345 kJ/kg for the cyclone materials; and 12 to 132 kJ/kg for the baghouse materials. These values are comparable to those in the previous study, except for the lower heats of reaction of some of the Queen's cyclone and baghouse materials, and of the Summerside baghouse material.

The results of the previous study indicated that the exothermic nature of these residues is largely due to the hydration of calcium oxide (also known as quicklime or unslaked lime). Although no calcium oxide analyses were conducted in this study, the

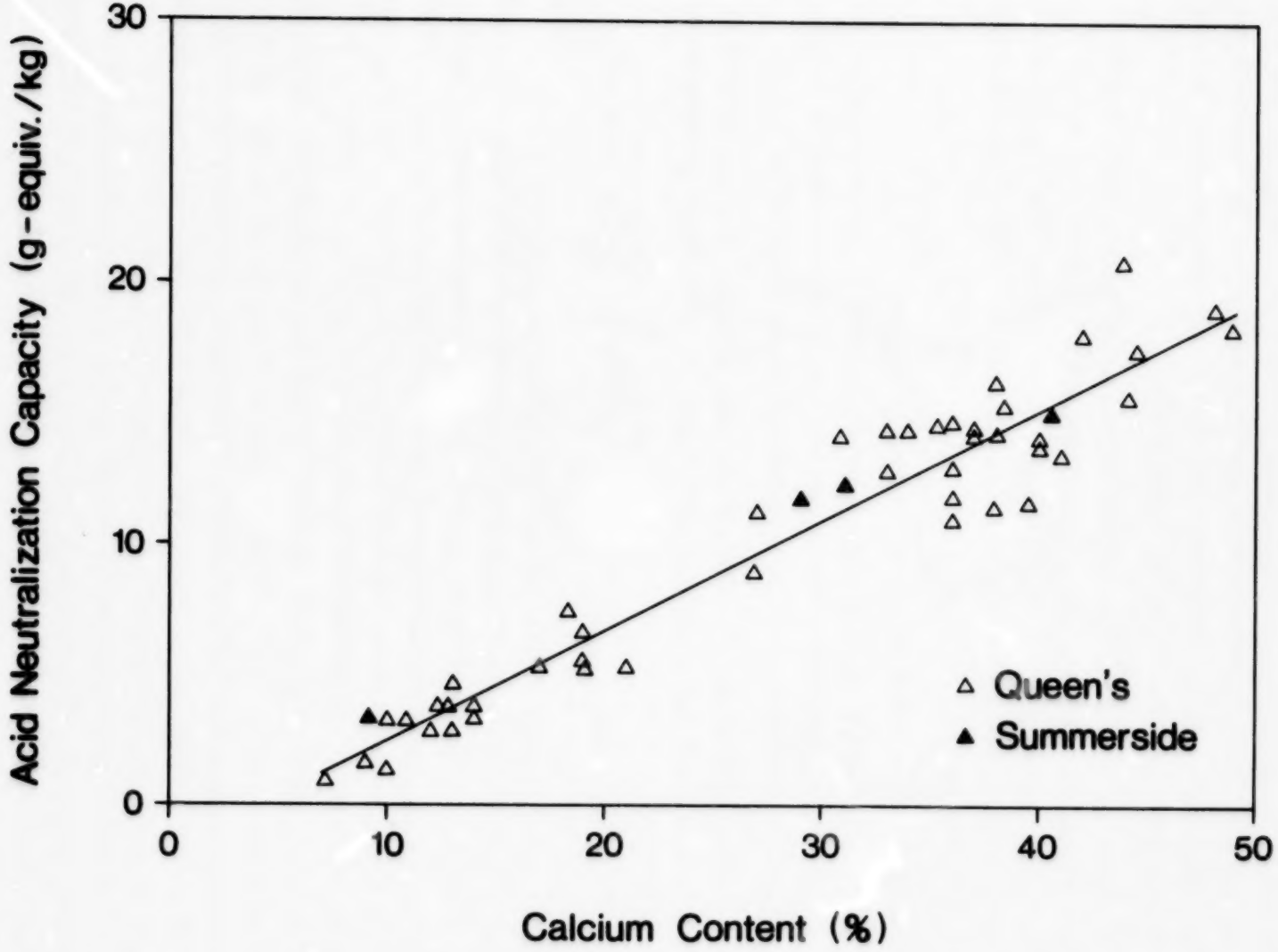

FIGURE 4 ACID NEUTRALIZATION CAPACITY VERSUS CALCIUM CONTENT

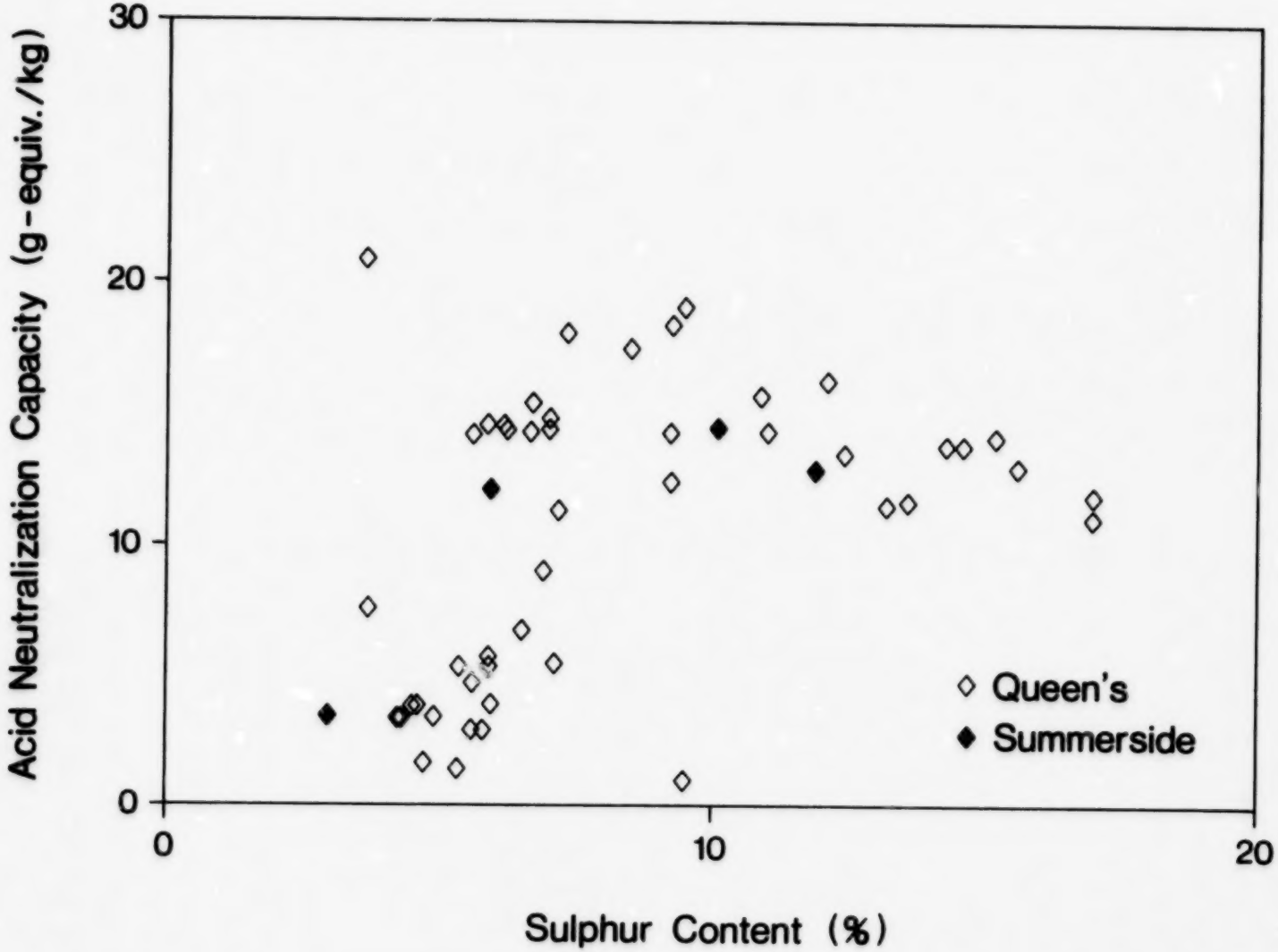

FIGURE 5 ACID NEUTRALIZATION CAPACITY VERSUS SULPHUR CONTENT

TABLE 12 RESULTS OF CALORIMETER TESTS

		Bed Material			Cyclone Material			Baghouse Material		
Run No.	Liquid-to Solid Ratio	T (K)	t (min)	-ΔH (kJ/kg)	T (K)	t (min)	-ΔH (kJ/kg)	T (K)	t (min)	-ΔH (kJ/kg)
840111E	10:1	9.0	120	411	7.0	90	319	3.0	90	137
	5:1	17.5	90	399	12.5	90	285	6.0	210	137
	3:1	29.0	60	397	20.0	60	274	9.0	180	123
	Mean			402			293			132
840117E	10:1	7.5	90	343	2.0	60	91	0.0	-	0
	5:1	15.0	90	343	4.0	120	91	1.0	30	23
	3:1	42.5	60	582	7.0	390	96	1.0	30	14
	Mean			423			93			12
840124E	10:1	7.0	150	320	7.0	120	320	2.0	60	91
	5:1	13.5	150	308	12.5	120	285	4.5	90	103
	3:1	22.5	90	308	24.0	90	329	6.5	150	89
	Mean			312			311			94
840126E	10:1	9.0	240	410	7.0	60	320	1.5	30	69
	5:1	13.0	120	270	14.0	60	320	2.5	60	57
	3:1	23.5	120	322	22.5	60	308	3.5	60	48
	Mean			334			316			58
840207E	10:1	6.0	240	274	6.5	150	297	0.5	30	23
	5:1	10.5	240	240	9.5	90	217	0.5	30	11
	3:1	17.5	240	240	15.5	60	212	0.5	30	7
	Mean			251			242			14
840215E	10:1	9.0	150	411	7.5	90	343	1.0	30	46
	5:1	18.0	120	411	14.5	90	331	2.0	30	46
	3:1	31.0	60	423	23.5	60	322	2.5	60	34
	Mean			415			332			42
840216E	10:1	7.0	270	320	7.5	90	343	1.5	30	69
	5:1	10.0	180	228	13.5	60	308	2.5	60	57
	3:1	20.5	150	281	24.5	60	335	3.0	60	41
	Mean			276			329			56
840313E	10:1	6.5	120	297				2.0	90	91
	5:1	12.0	180	274	No Sample Available			3.0	90	69
	3:1	21.0	150	288				4.5	60	62
	Mean			286						74
840314E	10:1	5.5	120	251	8.0	90	365	0.5	30	23
	5:1	13.5	180	308	15.0	60	343	1.0	30	23
	3:1	23.5	90	322	24.0	60	329	2.0	60	27
	Mean			294			346			24
840320E	10:1	5.5	150	251	3.5	90	160	0.5	60	23
	5:1	11.5	210	263	7.0	180	160	0.5	30	11
	3:1	18.5	120	253	9.5	210	130	1.0	30	14
	Mean			256			150			16
841104D	10:1	4.5	120	206				1.5	30	69
	5:1	12.0	150	274	No Sample Available			2.5	30	57
	3:1	21.0	150	288				3.5	60	48
	Mean			256						58

Run Number = Year Month Day; Coal (E = Evans, D = Devco)
T = maximum temperature increase
t = elapsed time at which maximum temperature occurred
-ΔH = heat of reaction

previous results suggested that the lower heat of reaction of some of the residues was due to their lower unslaked lime content. The lower heats of reaction of the baghouse materials from Runs 840207E, 840314E and 840320E may also have been at least partially due to their hydration prior to testing, as indicated by their moisture contents in Table 4. Although the moisture contents of the rest of the samples were less than 1%, many of the materials were found to be hygroscopic when heated, and it is possible that some hydration of these samples occurred prior to exothermic testing.

In addition to the relationship between heat of reaction and calcium oxide content, the results of the previous study indicated a strong linear relationship between heat of reaction and acid neutralization capacity. This relationship was examined further by repeating the linear regression analyses using all the data from this and the previous study. The results, shown in Figure 6, indicate a strong correlation between the two variables. The correlation coefficient for the regression line in Figure 6 is 0.97.

The tests were conducted at liquid-to-solid ratios of 3:1, 5:1 and 10:1. As expected, temperature increases were generally greatest at the 3:1 ratio and least at the 10:1 ratio, since more residue was available for reaction at the lower liquid-to-solid ratio. Maximum temperature increases at the 3:1 ratio ranged from 18 to 43°C in the bed materials, 7 to 25°C in the cyclone materials, and 0.5 to 9°C in the baghouse materials. These values are similar to those measured in the previous study, except that the maximum temperature increase in the Summerside baghouse material in the previous study was much higher at 19°C.

The elapsed time required to reach the maximum heat of reaction varied widely, from 60 to 270 minutes for bed materials, 60 to 390 minutes for cyclone samples and 30 to 210 minutes for baghouse residues. Elapsed times to maximum temperature were usually least for the baghouse materials and greatest for the bed materials. This is consistent with lime slaking theory which states that the rate of reaction with water generally increases with increasing surface area (Kunesh, 1976).

3.3.2 Column Exothermic Tests. The exothermic properties of some of the residues was also examined by filling a column with residue, adding water slowly to the top, and monitoring temperature changes at various depths of residue. These tests were conducted to examine exothermic reactions of larger masses of residue under different slaking conditions than those experienced in the calorimeter test, and to give some indication of what might happen in a field disposal situation where a pile of dry material was exposed to rain.

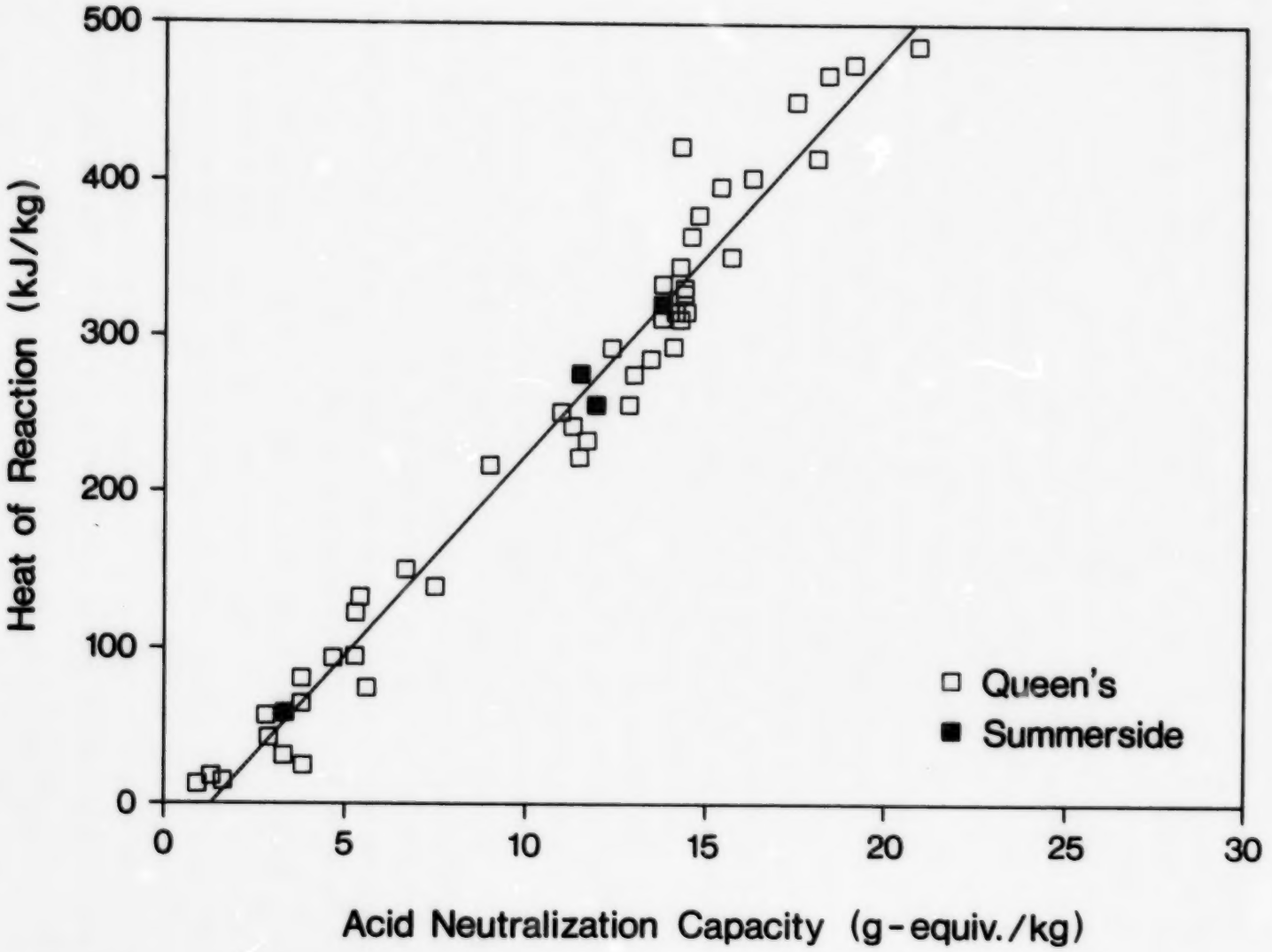

FIGURE 6 HEAT OF REACTION VERSUS ACID NEUTRALIZATION CAPACITY

The temperatures at the five thermocouples during the column exothermic tests are presented in Figures 7 and 8. The thermocouples were positioned at 4-cm intervals throughout the column, with Thermocouple No. 1 about 4 cm below the surface of the residue. The reproducibility of duplicate tests performed on the same material was usually very good, particularly with respect to the maximum temperature increases achieved in the column. Maximum temperature increases ranged from 102°C to 142°C in the bed materials and from 4°C to 72°C in the baghouse materials.

Temperature peaks at the thermocouples were reached sequentially from the top to the bottom of the column at approximately equal intervals. If a direct correlation between the achievement of a temperature peak and the position of the wetting front is assumed, it can be indicated that the liquids percolated through the materials at relatively uniform rates. The average intervals between peaks ranged from 42 minutes for the Run 841104D bed material to 71 minutes for the Run 840117E baghouse material. Since each thermocouple was 4 cm apart, this indicates that the liquids flowed through the materials at average rates of 1.6×10^{-3} to 9.4×10^{-4} cm/s. Unlike the 1982/83 study, where the flow rates in the column were an order of magnitude less than the coefficients of permeability, the flow rates in the bed materials were of the same order of magnitude as their coefficients of permeability (Table 6), except for Run 840117E bed material, which had a coefficient of permeability of 8.79×10^{-5} cm/s and an average flow rate in the column of 1.0×10^{-3} cm/s.

In the 1982/83 study, the highest temperatures were reached near the middle of the column. This was attributed to the ends of the column being open to the atmosphere, and the insulating effect of the ash and column walls near the middle of the column. Similar results were observed in some of the tests conducted during this study; however, in some cases the highest temperatures were recorded at the bottom thermocouple (e.g., for the bed and baghouse materials from Run 841104D). In other cases, the highest temperatures were approximately the same at the bottom four thermocouples (e.g., for baghouse material from Run 831124D and bed material from Run 840117E). These different patterns of temperature peaks with residue depth probably occurred because the wire screen at the base of the column was replaced in this study with a perforated stainless steel plate. The results suggest that even higher maximum temperature increases might be reached in some materials if the length of the column apparatus was extended. Extrapolating this to a field situation suggests that maximum temperatures reached within piles of some types of AFBC residues exposed to rain would increase as the sizes of the piles increased.

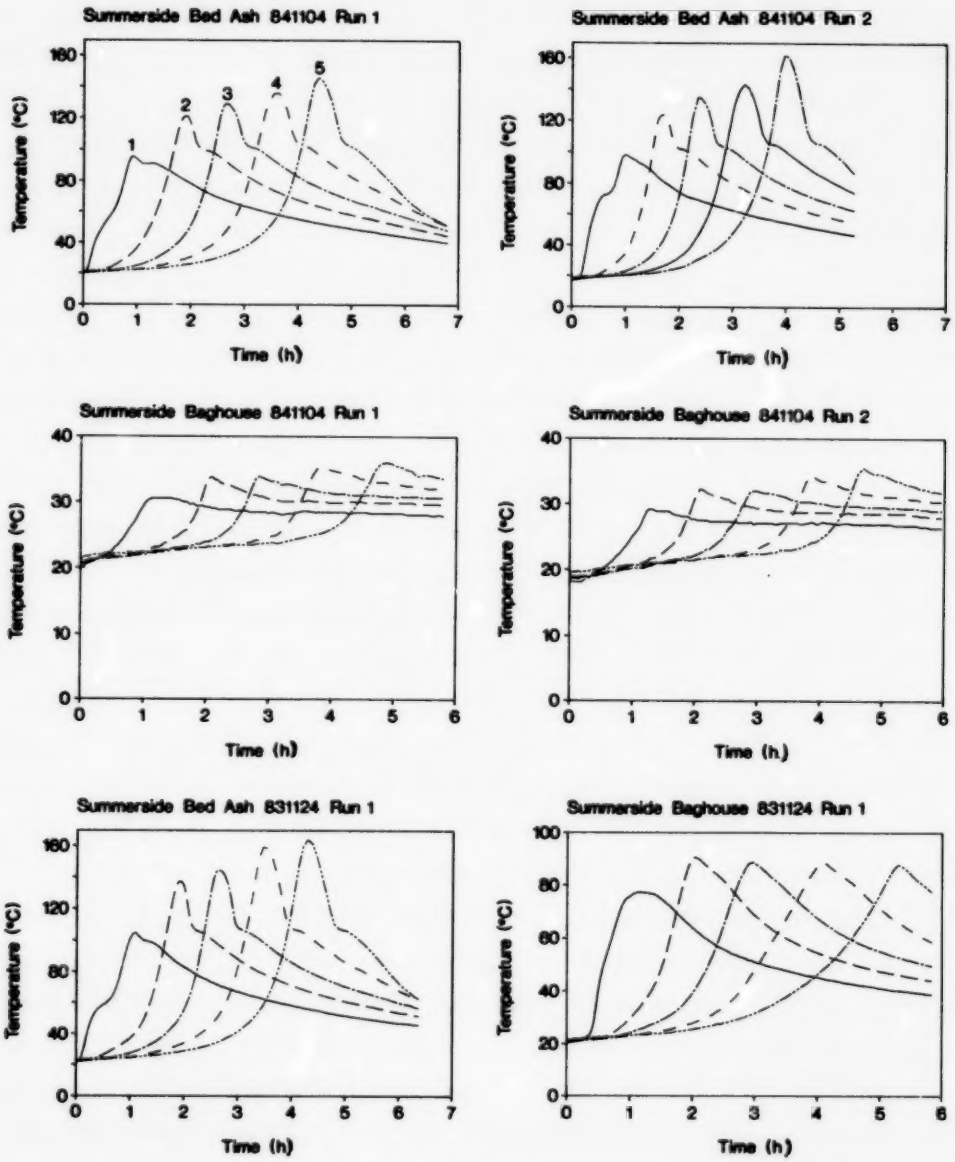

FIGURE 7 **RESULTS OF COLUMN EXOTHERMIC TESTS ON SUMMERSIDE MATERIALS**

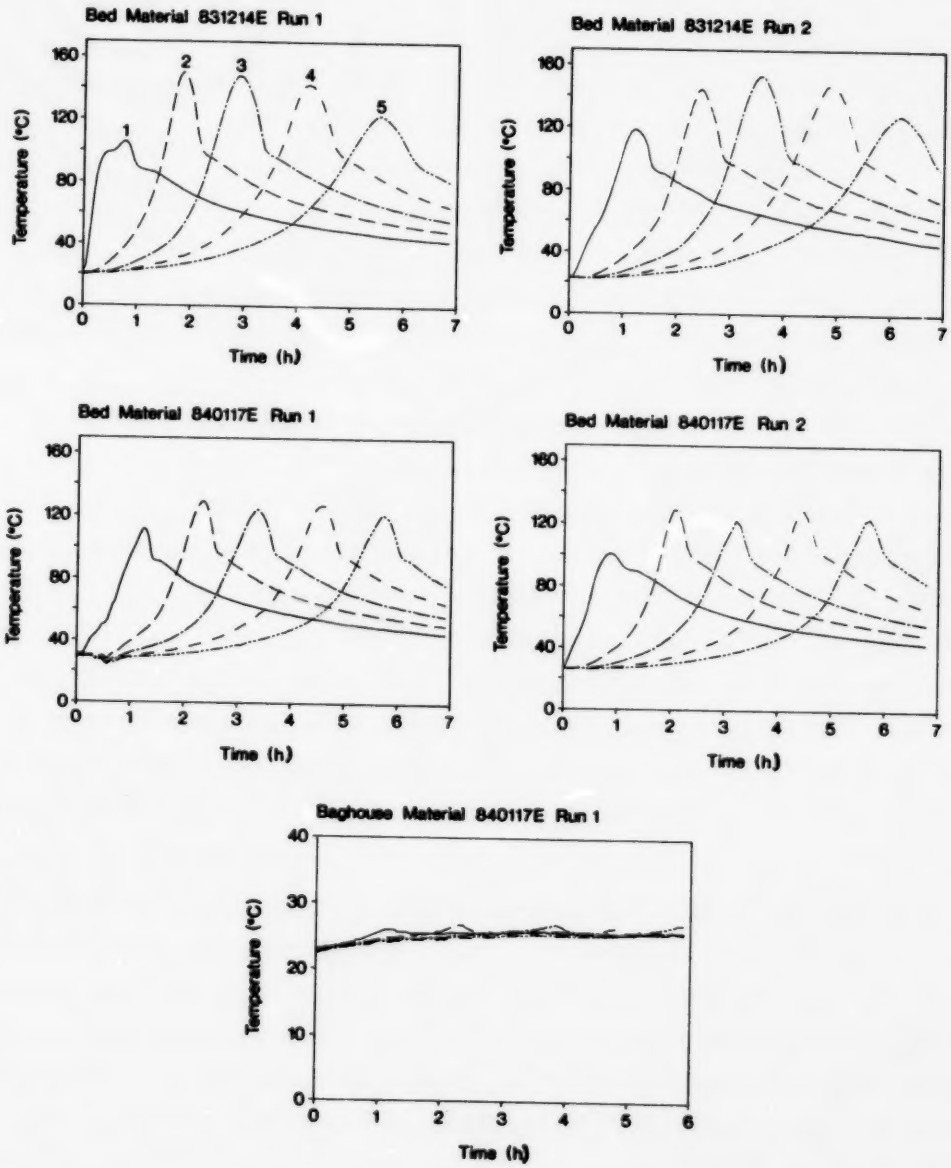

FIGURE 8 RESULTS OF COLUMN EXOTHERMIC TESTS ON QUEEN'S MATERIALS

A scattergram of the average maximum temperature increase measured in the column tests to the average heat of reaction is shown in Figure 9. Some correlation is apparent if all test results are considered; however, there is no correlation between the variables if only the bed material results are compared.

3.4 Leaching Properties

3.4.1 Batch Leaching Tests. The results of the serial batch leaching tests are found in the Appendix (Tables A.1 to A.4). The results given under "Trial 1" for the bed and baghouse materials from Run 831214E were taken from the previous study.

The results are comparable to those obtained in the previous batch leaching tests conducted on the Queen's and Summerside materials. All leachates remained highly alkaline throughout the 20 leaching cycles. Total dissolved solids (TDS) concentrations in the first cycle were typically about 5000 mg/L. TDS levels in the bed material leachates remained high during the first several cycles then decreased. TDS levels in the baghouse material leachates decreased steadily throughout the 20 cycles. The major constituents in the leachates were calcium and sulphate. The concentrations of these constituents were typically several orders of magnitude greater than those of the other elements in the leachates. The concentrations of calcium and sulphate in the bed material leachates are plotted versus cumulative liquid-to-solid ratio in Figures 10 and 11. The good agreement between the two trials conducted on the materials from Runs 831214E and 840117E indicates that the reproducibility of the batch test procedure is very good.

Weight loss over the 20 leaching cycles was determined by weighing the residues before and after the tests. Average weight losses were 72.2% and 65.4% in the bed materials from Runs 831214E and 840117E, respectively, and 27% in the baghouse material from Run 831214E. These values are comparable to those obtained in the previous study.

3.4.2 Column Leaching Tests. Column leaching tests were conducted to determine if the different configuration of the residue (i.e., compacted within a column instead of suspended within the leaching medium) and the method of contacting the residue with water (i.e., slow percolation through a column open to the atmosphere instead of continuous mixing within a sealed container) would have any influence on leachability. The results of the tests are given in the Appendix (Tables A.5 to A.13).

Each column contained approximately 330 cm^3 of residue. Pore volumes measured at the beginning of the tests ranged from 50 to 60% in the bed material

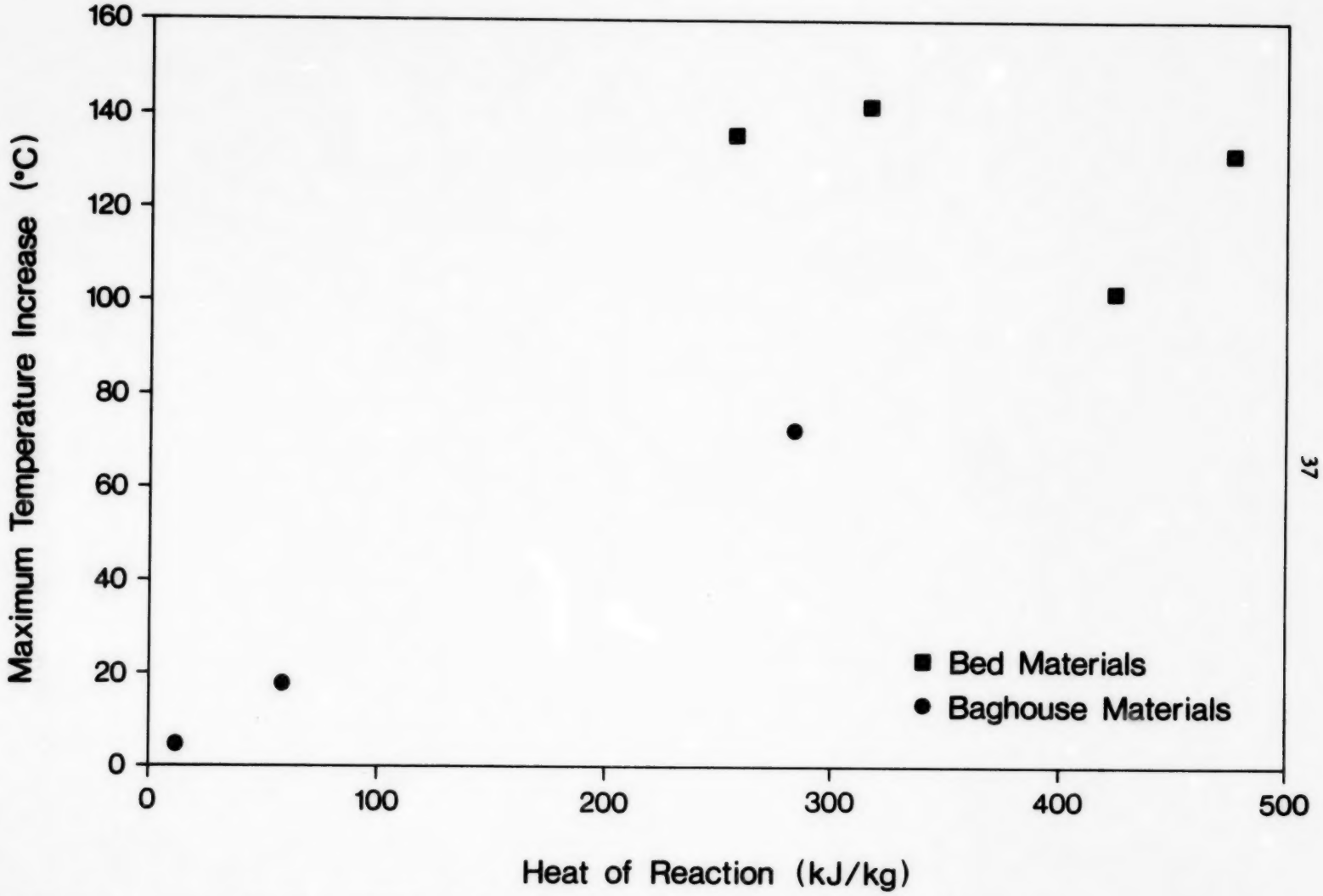

FIGURE 9 MAXIMUM TEMPERATURE INCREASE IN COLUMN VERSUS HEAT OF REACTION

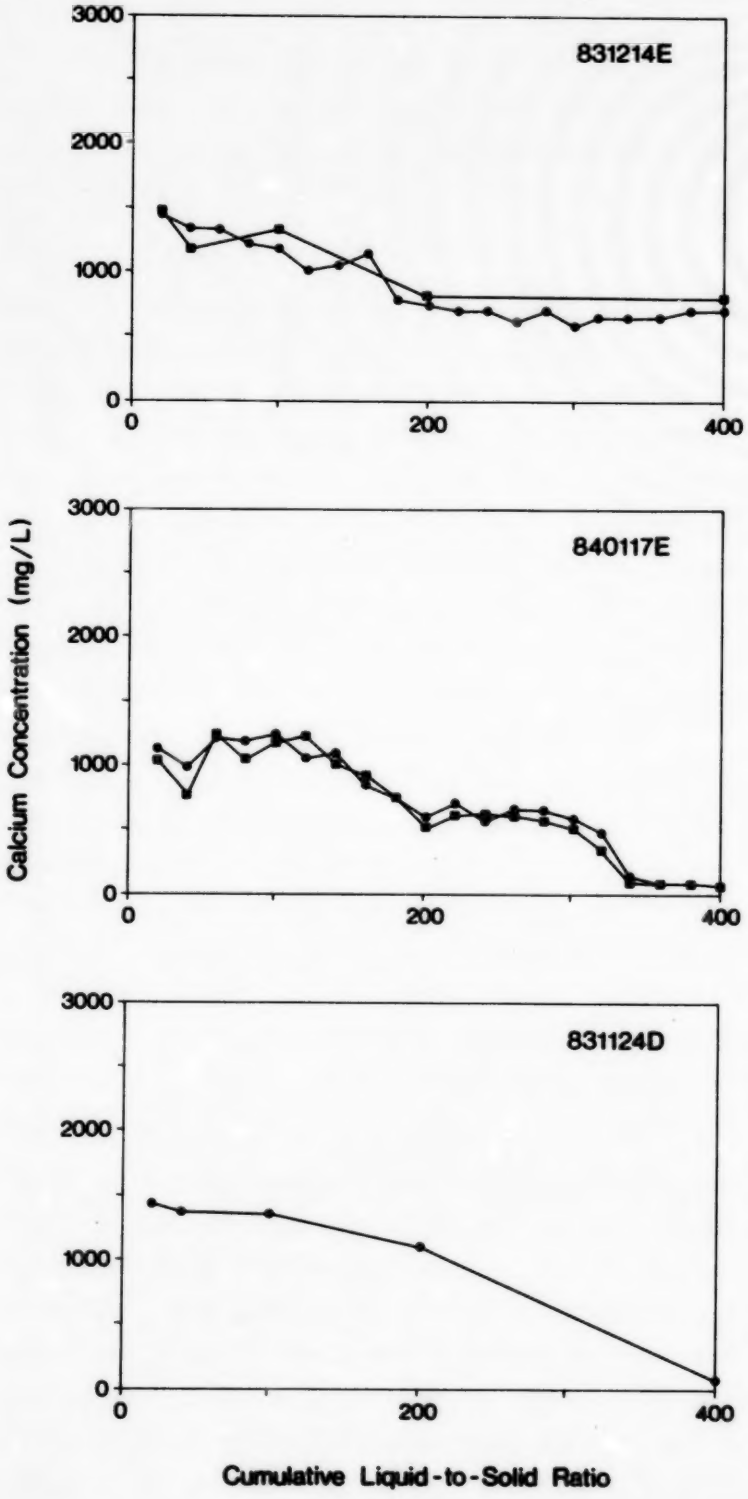

FIGURE 10 CALCIUM CONCENTRATIONS IN BATCH TEST LEACHATES FROM BED MATERIALS

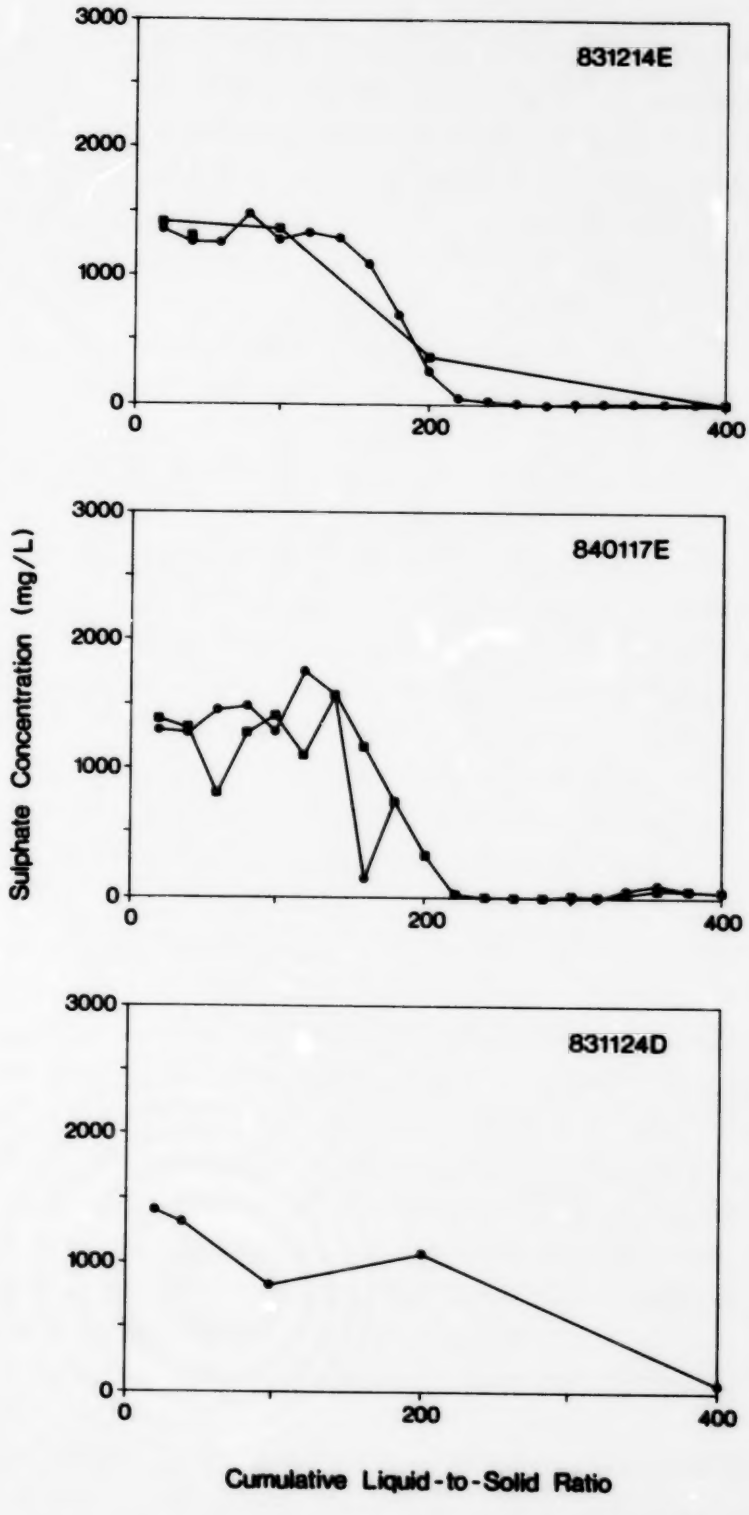

FIGURE 11 SULPHATE CONCENTRATIONS IN BATCH TEST LEACHATES FROM BED MATERIALS

columns, 60 to 70% in the baghouse material columns, and 60 to 65% in the columns containing a mixture of bed and baghouse materials.

Problems were encountered with the columns containing baghouse materials shortly after the tests were begun. All flow through these columns ceased after only 2 to 3 pore volumes of leachate had been collected. Although a head of water was subsequently maintained on top of these columns for three months, no additional leachate was collected.

The baghouse material columns were then emptied and replaced with 1:1 mixtures of bed and baghouse materials; however, water flow through these columns also ceased after 3 to 9 pore volumes of leachate had been collected.

After several months of testing, hairline stress cracks were observed in all of the acrylic columns. These cracks were more extensive in the columns containing the mixtures of bed and baghouse materials. Eventually two of the columns containing bed/baghouse mixtures from Run 840117E split open.

A problem was also encountered with the "Trial 1" column containing bed material from Run 831124D. It had to be discontinued after 51 pore volumes of leachate generation because of oil contamination in the tubing from the peristaltic pump.

Another problem was the occurrence of channeling in all the bed material columns. This may have resulted in underestimation of the leachability of the bed residues since the applied water was able to flow through a column without contacting all of its contents.

The calcium and sulphate concentrations in the column test leachates versus cumulative liquid-to-solid ratio are shown in Figures 12 to 17. The results from the first cycles of the batch leaching tests are also shown for comparison. The sulphate concentrations in the leachates from both types of tests were approximately equal at equivalent liquid-to-solid ratios. The calcium concentrations in leachates from the first cycle of the batch leaching tests were comparable to the average concentrations in the column test leachates during the same period. Subsequent calcium concentrations in the column test leachates, however, were much less than those in the batch test leachates. A similar trend is apparent in the TDS concentrations. Although the lower values in the column test leachates may be attributable to channeling, this is doubtful because of the good agreement between the sulphate concentrations in leachates from the two types of tests.

The decreased water flow, the appearance of stress cracks in all columns and the eventual splitting of some columns suggest that reactions continued to occur in the

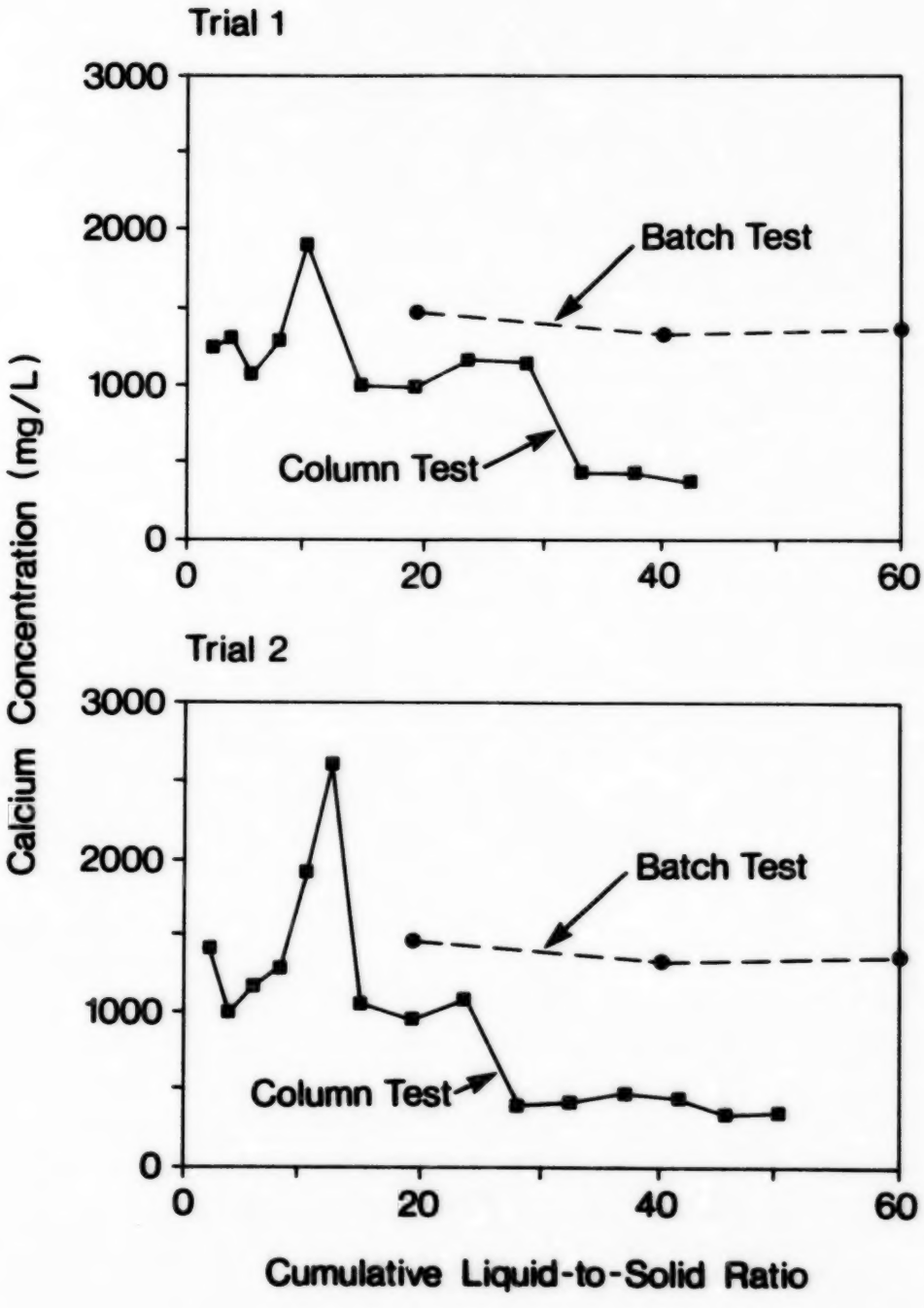

FIGURE 12 CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831214E BED MATERIAL

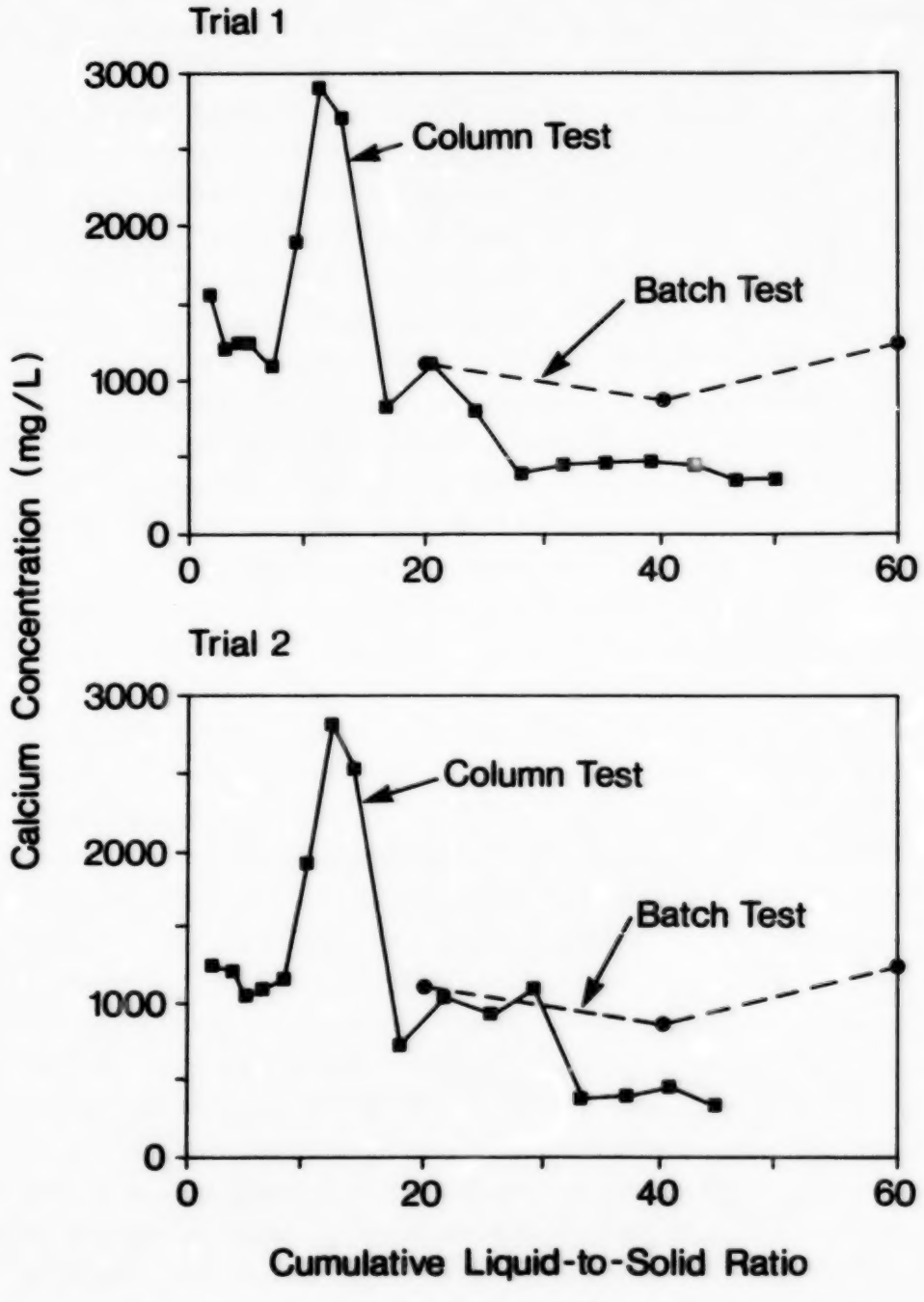

FIGURE 13 CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 840117E BED MATERIAL

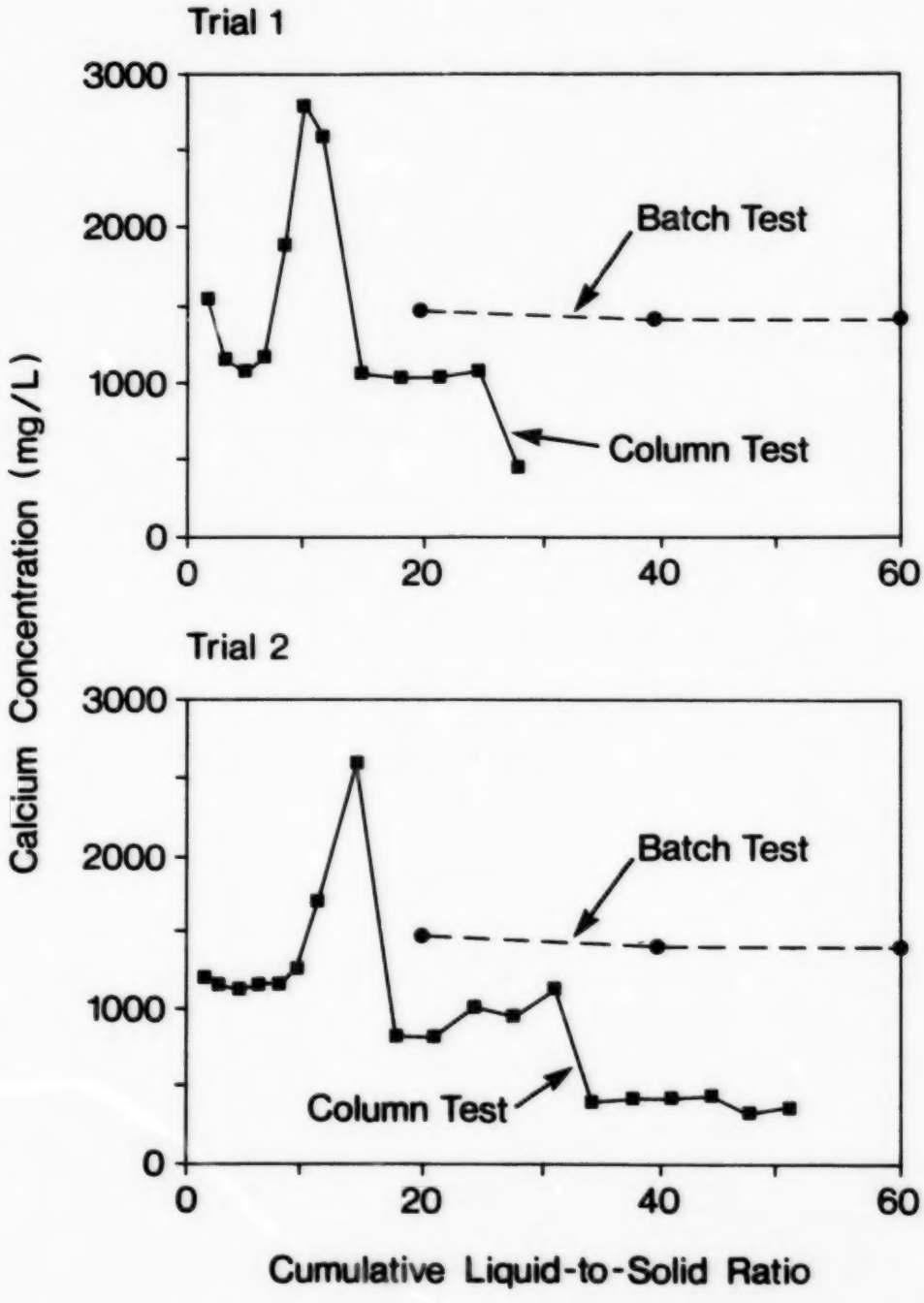

FIGURE 14 CALCIUM CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831124D BED MATERIAL

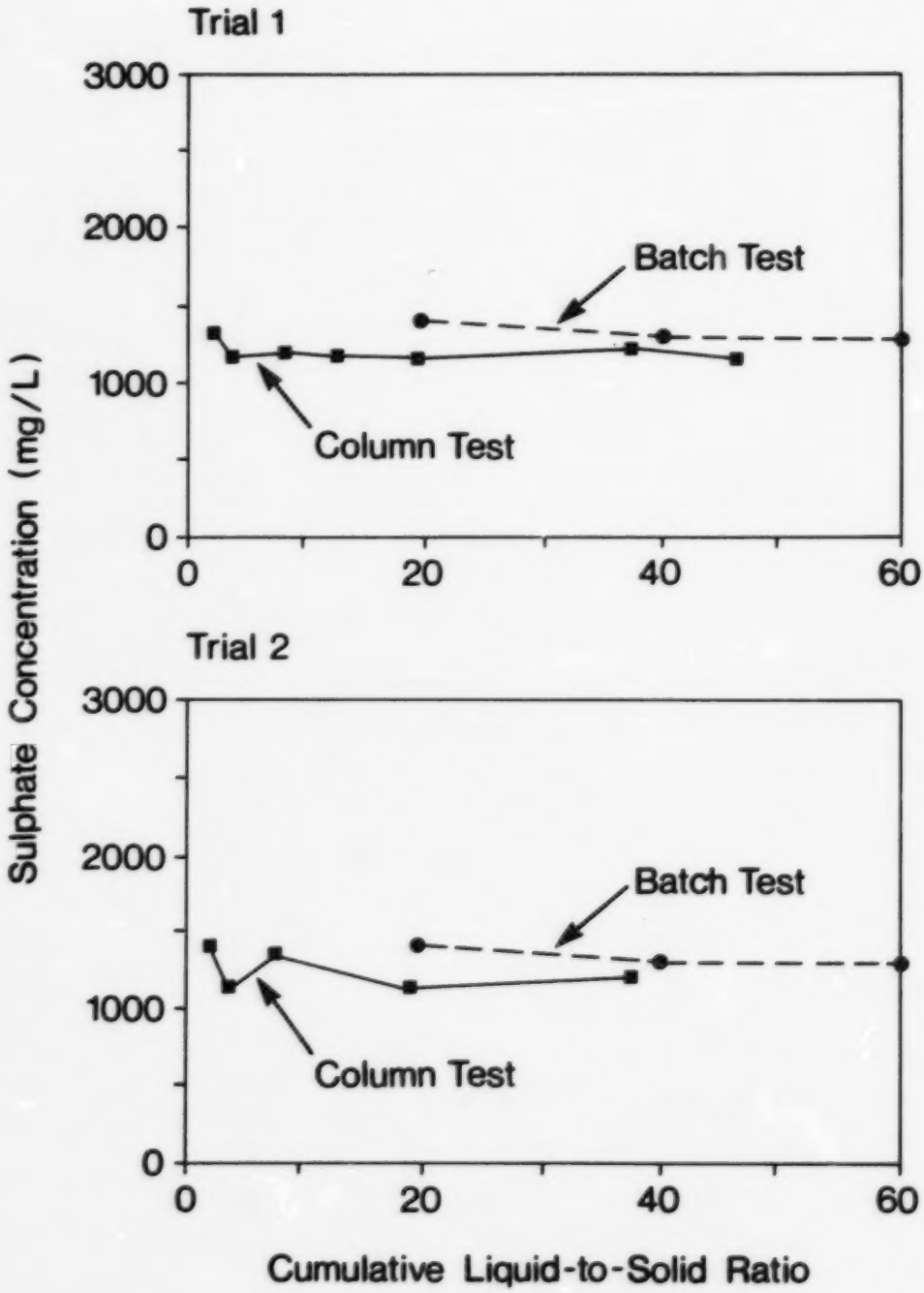

FIGURE 15 SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831214E BED MATERIAL

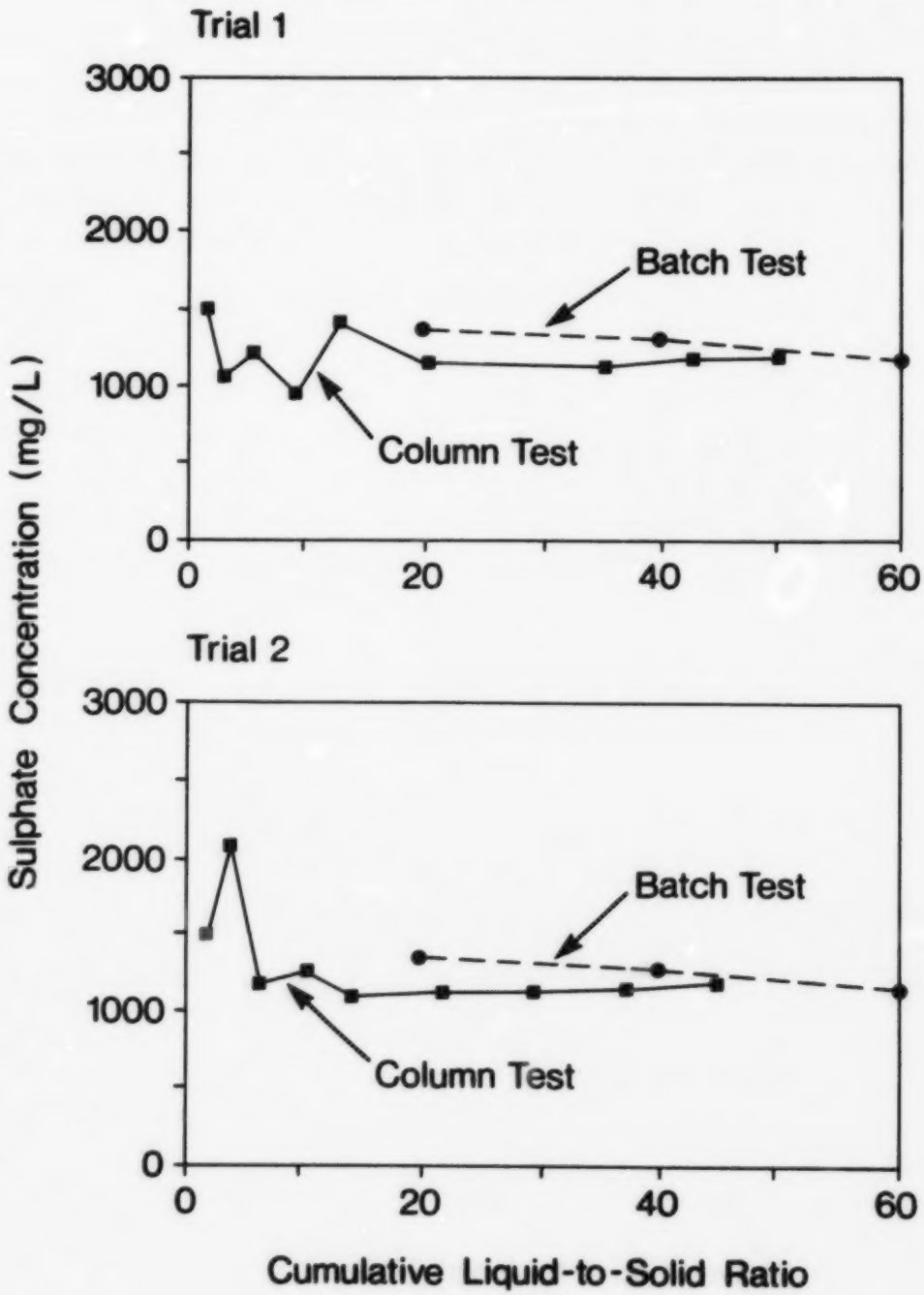

FIGURE 16 SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 840117E BED MATERIAL

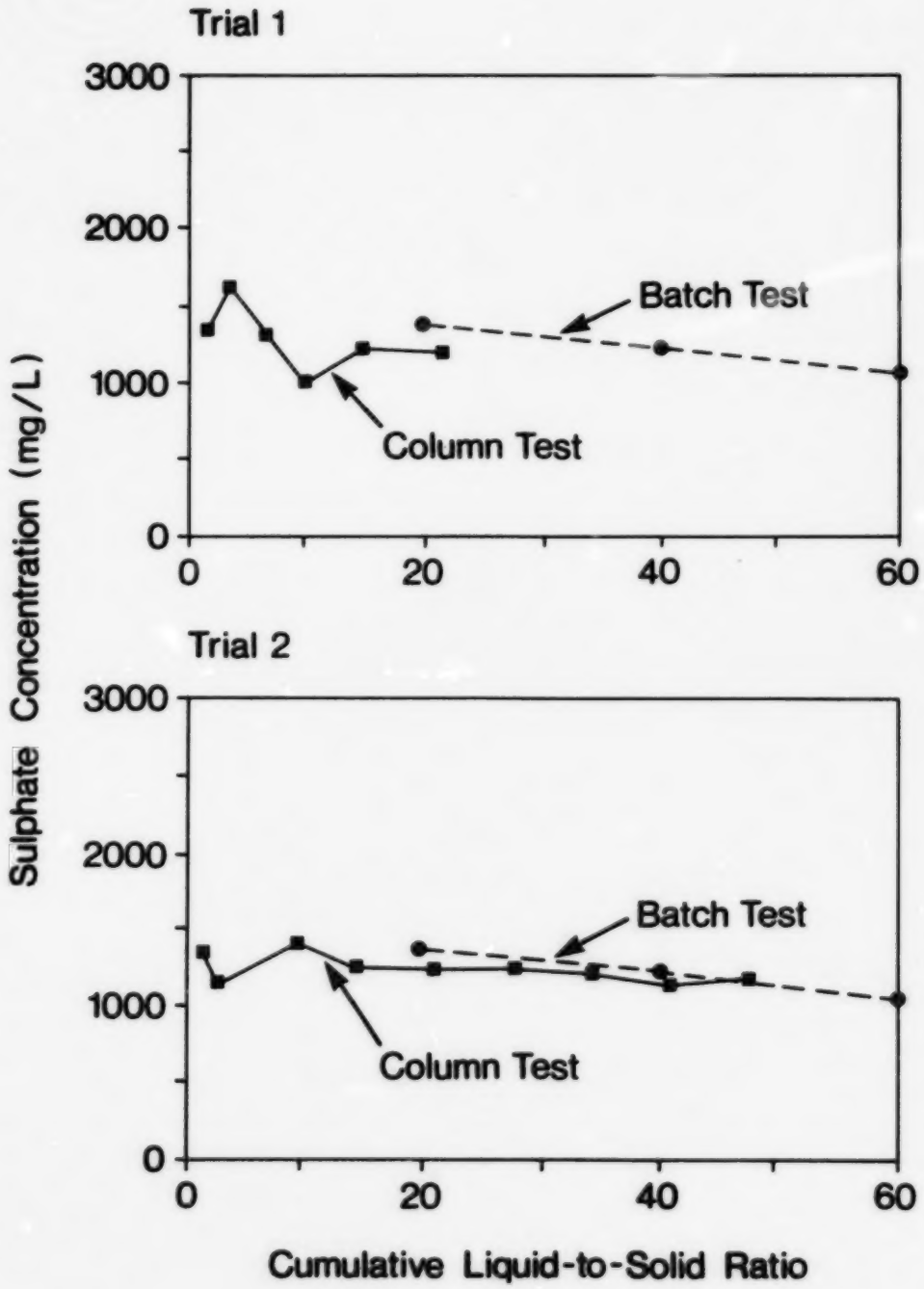

FIGURE 17 SULPHATE CONCENTRATIONS IN COLUMN TEST LEACHATES FROM RUN 831124D BED MATERIAL

previously hydrated and dried residues for several months. These results are consistent with observations made at the Summerside site that the disposed residues slowly hardened to become large rock-like masses which were strong enough to be moved around by bulldozer without breaking apart (R. Kissel, personal communication, 1985). Since the column leaching tests are more representative of field disposal conditions than the batch leaching tests, it appears that the leachability of the baghouse materials was grossly overestimated in the batch leaching tests used in this study and the previous studies.

3.5 Quality Control

A quality control/quality assurance program was conducted on the solid and leachate analyses using standards, blanks, spiked samples and replicate analyses. Seven standards containing Al, Ba, B, Ca, Cu, Fe, Mg, Ni, K, Si, Na and Zn were prepared to represent the metal concentrations and matrix expected in the leachate samples. The standards were submitted as blinds at various times during the study. Percent recovery of metals generally ranged from 80% to 130%. Percent relative standard deviations were less than 30% in most cases.

As in the previous studies, a standard reference PCF fly ash was used in the solid material quality control program. The results were comparable to those obtained in the other studies.

4 SUMMARY

This study was conducted to continue development of a data base on the properties of AFBC wastes. Solid residues from the Queen's University and CFB Summerside AFBC units were subjected to a battery of tests and analyses to measure their physical, chemical, leaching and exothermic properties. Most of the tests were similar to those used in two previous AFBC waste characterization studies. Additional tests, such as unconfined compressive strength, column leaching and bulk density, were conducted during this study to provide information on other characteristics of the wastes.

In general, the results of this study confirmed the findings of the previous studies. The residues were highly buffered and composed primarily of calcium and sulphur salts. They were exothermic and swelled considerably when in contact with water. Their leachates were highly alkaline with high total dissolved solids concentrations; however, the results of column leaching tests conducted in this study suggest that the bed and baghouse materials are not as readily soluble in a field disposal situation as they were indicated to be in previous studies which only employed batch leaching tests. It appears that reactions continue to occur in the wastes for several months after disposal until the residues eventually solidify.

Other new information arising from this study indicates that the residues should be hydrated, dried (if necessary) to between 20% and 50% moisture, and compacted (e.g., by earthmoving equipment) prior to final disposal in a landfill. This would delay the commencement of leachate release from the landfill, decrease disposal volume requirements, and decrease the permeability of the residues (i.e., decrease the leachate production rate).

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APPENDIX
TEST RESULTS

TABLE A.1 RESULTS OF BATCH LEACHING TESTS ON BED MATERIAL FROM RUN 831214E

Cycle	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Mn	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
1	20	12.50	8.84	4480	<0.01	0.044	0.19	1480	9.6	<0.009	0.11	<1	<0.01	<1	0.07	<0.05	1420	1.50	<0.005	0.09
2	40	12.50	8.80	4470	<0.01	0.037	<0.005	1190	8.6	0.012	0.13	<1	<0.01	<1	0.06	<0.05	1300	0.57	<0.005	0.06
3	60	12.70	8.90	4300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	80	12.70	8.80	4310	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	100	12.40	8.70	4370	<0.01	0.029	<0.005	1350	3.5	0.011	0.11	<1	<0.01	<1	0.07	<0.05	1360	0.23	<0.005	0.08
6	120	12.60	8.50	4210	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	140	12.70	8.20	4090	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	160	12.50	8.50	3640	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	180	12.50	8.20	3820	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	200	12.40	7.97	2390	<0.01	0.022	<0.005	825	1.2	0.009	0.06	<1	<0.01	<1	<0.05	<0.05	357	<0.001	<0.005	<0.05
11	220	12.60	7.50	2030	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	240	12.50	7.50	1960	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	260	12.60	7.20	1880	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	280	12.60	7.20	1810	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	300	12.60	7.20	1840	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	320	12.50	7.20	1790	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	340	12.50	7.00	1750	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	360	12.50	7.20	1780	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	380	12.20	7.20	1740	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	400	12.40	7.20	1730	<0.01	0.016	<0.005	807	0.7	<0.009	0.03	<1	<0.01	<1	<0.05	<0.05	6	<0.001	<0.005	0.06
Trial 2																				
1	20	12.37	9.64	5020	0.11	0.05	0.13	1460	10.0	0.03	0.11	0.46	0.03	0.74	<0.01	0.1	1370	0.92	0.01	0.04
2	40	12.38	9.57	5030	0.11	0.03	0.06	1350	1.0	0.03	0.14	0.08	0.04	0.14	<0.01	0.2	1280	0.52	0.01	0.05
3	60	12.38	9.40	5090	-	-	-	1350	1.0	-	-	-	-	-	-	-	1260	-	-	-
4	80	12.27	9.38	4930	-	-	-	1240	0.7	-	-	-	-	-	-	-	1490	-	-	-
5	100	12.19	9.42	4530	<0.05	0.06	0.04	1190	1.0	0.03	0.12	<0.04	0.04	<0.02	<0.01	0.4	1280	0.40	0.03	0.03
6	120	11.96	9.51	4290	-	-	-	1010	1.0	-	-	-	-	-	-	-	1350	-	-	-
7	140	12.18	9.19	3630	-	-	-	1060	0.7	-	-	-	-	-	-	-	1300	-	-	-
8	160	12.16	8.92	4010	-	-	-	1150	<0.1	-	-	-	-	-	-	-	1100	-	-	-
9	180	12.20	8.71	3300	-	-	-	794	0.2	-	-	-	-	-	-	-	695	-	-	-
10	200	12.20	8.24	2400	<0.05	0.14	0.44	744	0.5	0.02	0.11	0.04	0.04	<0.02	<0.01	0.3	240	0.12	0.20	0.04
11	220	11.91	8.05	2060	-	-	-	784	<0.1	-	-	-	-	-	-	-	57	-	-	-
12	240	11.94	7.85	1980	-	-	-	786	<0.1	-	-	-	-	-	-	-	22	-	-	-
13	260	11.87	7.73	1900	-	-	-	617	<0.1	-	-	-	-	-	-	-	9.1	-	-	-
14	280	12.01	7.70	1920	-	-	-	706	<0.1	-	-	-	-	-	-	-	4.6	-	-	-
15	300	11.98	7.56	1900	-	-	-	595	<0.1	-	-	-	-	-	-	-	6.9	-	-	-
16	320	12.14	7.56	1920	-	-	-	661	<0.1	-	-	-	-	-	-	-	7.5	-	-	-
17	340	12.12	7.50	1890	-	-	-	661	<0.1	-	-	-	-	-	-	-	16	-	-	-
18	360	12.16	7.50	1920	-	-	-	661	<0.1	-	-	-	-	-	-	-	12	-	-	-
19	380	12.13	7.45	1830	-	-	-	706	0.2	-	-	-	-	-	-	-	7.0	-	-	-
20	400	11.89	7.35	1740	<0.10	0.03	0.03	706	<0.1	0.03	0.09	0.25	0.03	0.16	<0.02	0.3	4.0	<0.02	0.02	0.04

All results given in mg/L except pH and conductivity (mS/cm).
Weight loss over 20 leaching cycles: 72.4% in Trial 1 and 72.0% in Trial 2.

TABLE A.2 RESULTS OF BATCH LEACHING TESTS ON BAGHOUSE MATERIAL FROM RUN 831214E

Cycle	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
1	20	12.50	10.49	5460	<0.01	0.079	0.562	1790	272	0.012	0.11	45	<0.01	86	0.07	0.11	1600	1.42	<0.005	0.23
2	40	12.50	8.84	4300	<0.01	0.040	0.358	1410	42.9	0.029	0.12	5	<0.01	13	0.06	<0.05	1730	0.56	<0.005	0.13
3	60	12.70	7.80	4120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	80	12.60	7.30	3600	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	100	11.50	2.07	1300	<0.01	0.024	0.122	315	3.6	<0.009	0.04	9	0.09	11	<0.05	5.69	740	0.91	0.08	<0.05
6	120	11.70	1.05	436	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	140	11.50	0.74	284	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	160	11.60	0.64	194	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	180	11.50	0.57	220	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	200	11.20	0.55	226	0.93	0.211	0.053	45.2	1.3	<0.009	0.02	2	0.07	2	<0.05	1.05	70	0.04	0.10	<0.05
11	220	11.40	0.55	206	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	240	11.40	0.49	244	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	260	11.40	0.48	240	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	280	11.40	0.47	218	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	300	11.30	0.46	234	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	320	11.30	0.47	216	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17	340	11.30	0.46	194	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	360	11.20	0.46	174	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	380	10.90	0.46	168	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	400	10.90	0.42	170	4.43	0.130	0.092	61.8	2.3	<0.009	<0.01	<1	0.02	<1	<0.05	3.7	58	0.09	0.05	<0.05
Trial 2																				
1	20	12.23	11.66	5860	0.09	0.07	0.13	1200	339	0.03	0.12	35.0	0.04	79.0	<0.01	0.4	1410	0.90	0.01	0.10
2	40	12.26	9.45	5000	0.10	0.05	0.20	936	59.2	0.03	0.10	3.70	0.03	11.0	<0.01	0.7	1400	0.52	<0.01	0.15
3	60	12.30	8.30	4500	-	-	-	1100	7.5	-	-	-	-	-	-	-	1440	-	-	-
4	80	12.22	4.62	2550	-	-	-	617	3.4	-	-	-	-	-	-	-	1520	-	-	-
5	100	11.20	1.25	910	0.60	0.07	0.14	159	3.6	<0.02	0.04	5.36	0.15	13.0	<0.01	6.4	360	0.50	0.42	0.01
6	120	11.29	0.79	465	-	-	-	90	1.4	-	-	-	-	-	-	-	235	-	-	-
7	140	11.30	0.64	394	-	-	-	69	0.9	-	-	-	-	-	-	-	135	-	-	-
8	160	11.35	0.57	306	-	-	-	63	0.5	-	-	-	-	-	-	-	75	-	-	-
9	180	11.15	0.55	356	-	-	-	63	0.7	-	-	-	-	-	-	-	30	-	-	-
10	200	11.22	0.51	324	4.10	0.01	0.48	53	0.6	<0.01	0.04	0.32	0.09	0.70	<0.01	2.1	43	0.06	0.04	0.02
11	220	10.91	0.48	302	-	-	-	57	<0.1	-	-	-	-	-	-	-	77	-	-	-
12	240	11.15	0.46	285	-	-	-	57	<0.1	-	-	-	-	-	-	-	71	-	-	-
13	260	11.03	0.44	299	-	-	-	53	<0.1	-	-	-	-	-	-	-	73	-	-	-
14	280	11.04	0.44	315	-	-	-	48	<0.1	-	-	-	-	-	-	-	73	-	-	-
15	300	11.03	0.41	260	-	-	-	43	<0.1	-	-	-	-	-	-	-	85	-	-	-
16	320	10.99	0.38	276	-	-	-	50	<0.1	-	-	-	-	-	-	-	85	-	-	-
17	340	10.90	0.35	254	-	-	-	42	<0.1	-	-	-	-	-	-	-	65	-	-	-
18	360	10.76	0.33	242	-	-	-	38	<0.1	-	-	-	-	-	-	-	63	-	-	-
19	380	10.79	0.33	218	-	-	-	44	<0.1	-	-	-	-	-	-	-	64	-	-	-
20	400	10.70	0.30	181	3.60	0.15	<0.02	45	<0.1	<0.01	0.04	0.20	0.06	2.88	<0.02	1.8	59	0.02	0.09	0.02

All results given in mg/L except pH and conductivity (mS/cm).
Weight loss over 20 leaching cycles: 30.4% in Trial 1 and 23.6% in Trial 2.

TABLE A.3 RESULTS OF BATCH LEACHING TESTS ON 1:1 MIXTURE OF BED AND BAGHOUSE MATERIALS FROM RUN 831214E

Cycle	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Mn	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
1	20	12.45	11.16	5600	0.08	0.08	0.12	1040	210	0.03	0.12	21.0	0.03	46	<0.01	0.7	1500	0.08	0.01	0.17
2	40	12.26	9.95	5020	0.07	0.05	0.30	900	30	0.03	0.16	1.84	0.02	3.5	<0.01	0.5	1420	0.46	<0.01	0.13
3	60	12.37	9.27	4850	-	-	-	1200	4.1	-	-	-	-	-	-	-	1470	-	-	-
4	80	12.30	9.05	4360	-	-	-	1100	2.7	-	-	-	-	-	-	-	1550	-	-	-
5	100	12.32	8.96	4100	<0.05	0.05	0.32	967	0.9	0.02	0.14	2.20	0.02	4.7	<0.01	0.3	1240	0.54	<0.01	0.05
6	120	12.29	8.82	3700	-	-	-	970	0.5	-	-	-	-	-	-	-	1020	-	-	-
7	140	12.31	8.27	3350	-	-	-	970	1.0	-	-	-	-	-	-	-	780	-	-	-
8	160	12.24	7.91	2370	-	-	-	750	0.4	-	-	-	-	-	-	-	205	-	-	-
9	180	12.20	7.64	1850	-	-	-	662	0.7	-	-	-	-	-	-	-	37.2	-	-	-
10	200	12.27	7.36	1700	0.20	0.17	6.67	521	0.8	0.02	0.08	3.50	0.04	7.5	<0.01	0.3	3.65	0.36	0.15	0.04
11	220	12.18	7.09	1630	-	-	-	573	<0.1	-	-	-	-	-	-	-	17.0	-	-	-
12	240	12.18	5.35	1340	-	-	-	441	<0.1	-	-	-	-	-	-	-	0.8	-	-	-
13	260	11.88	2.62	714	-	-	-	284	<0.1	-	-	-	-	-	-	-	13.3	-	-	-
14	280	11.71	1.51	394	-	-	-	168	<0.1	-	-	-	-	-	-	-	16.4	-	-	-
15	300	11.41	1.02	304	-	-	-	97	<0.1	-	-	-	-	-	-	-	44.4	-	-	-
16	320	11.33	0.85	340	-	-	-	70	<0.1	-	-	-	-	-	-	-	71	-	-	-
17	340	11.21	0.78	333	-	-	-	70	<0.1	-	-	-	-	-	-	-	60	-	-	-
18	360	11.30	0.71	331	-	-	-	66	<0.1	-	-	-	-	-	-	-	72	-	-	-
19	380	11.25	0.68	304	-	-	-	70	1.1	-	-	-	-	-	-	-	70	-	-	-
20	400	11.19	0.60	290	5.60	0.06	0.03	66	0.5	<0.01	0.04	0.74	0.04	1.0	<0.02	1.9	73	0.06	0.00	0.01
Trial 2																				
1	20	12.43	10.95	4990	0.07	0.07	0.14	1300	200	0.03	0.12	19.0	0.02	42.0	<0.01	1.0	1400	0.08	0.01	0.14
2	40	12.42	9.91	4900	<0.05	0.05	0.16	1040	33.2	0.03	0.10	2.14	0.02	4.4	0.03	0.3	1270	0.52	<0.01	0.17
3	60	12.42	9.26	4750	-	-	-	1200	4.5	-	-	-	-	-	-	-	1300	-	-	-
4	80	12.43	9.07	4440	-	-	-	1190	3.4	-	-	-	-	-	-	-	1330	-	-	-
5	100	12.33	8.96	4450	<0.05	0.06	0.29	810	1.3	0.02	0.08	1.60	0.02	4.3	<0.01	0.4	1240	0.52	<0.01	0.05
6	120	12.33	8.85	4160	-	-	-	1100	1.2	-	-	-	-	-	-	-	1040	-	-	-
7	140	12.34	8.32	3460	-	-	-	1060	0.6	-	-	-	-	-	-	-	775	-	-	-
8	160	12.38	8.00	2470	-	-	-	704	0.4	-	-	-	-	-	-	-	230	-	-	-
9	180	12.40	7.69	1910	-	-	-	643	2.1	-	-	-	-	-	-	-	29.8	-	-	-
10	200	12.31	7.42	1700	0.10	0.16	0.30	595	1.0	0.01	0.10	2.70	0.01	7.3	0.02	0.3	3.95	0.28	0.16	0.04
11	220	12.30	7.22	1730	-	-	-	573	<0.1	-	-	-	-	-	-	-	1.6	-	-	-
12	240	12.32	5.93	1460	-	-	-	441	<0.1	-	-	-	-	-	-	-	4.0	-	-	-
13	260	11.90	2.53	663	-	-	-	189	<0.1	-	-	-	-	-	-	-	0.3	-	-	-
14	280	11.72	1.39	373	-	-	-	100	<0.1	-	-	-	-	-	-	-	24.9	-	-	-
15	300	11.34	0.95	300	-	-	-	54	<0.1	-	-	-	-	-	-	-	44	-	-	-
16	320	11.30	0.80	333	-	-	-	70	<0.1	-	-	-	-	-	-	-	81	-	-	-
17	340	11.36	0.77	363	-	-	-	70	<0.1	-	-	-	-	-	-	-	75	-	-	-
18	360	11.28	0.70	331	-	-	-	70	<0.1	-	-	-	-	-	-	-	74	-	-	-
19	380	11.32	0.67	310	-	-	-	70	0.6	-	-	-	-	-	-	-	86	-	-	-
20	400	11.19	0.60	274	5.50	0.07	<0.02	66	0.9	<0.01	0.20	0.66	0.06	0.91	<0.02	1.9	86	0.06	0.00	0.03

All results given in ug/L except pH and conductivity (mS/cm).
Weight loss over 20 leaching cycles: 40.4% in Trial 1 and 43.2% in Trial 2.

TABLE A.4 BATCH LEACHING TESTS ON BED MATERIAL FROM RUN 840117E

Cycle	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
1	20	12.47	9.91	4650	0.07	0.09	0.20	1040	12.4	0.03	0.12	1.24	0.03	1.46	0.03	0.1	1400	0.08	0.03	0.13
2	40	12.46	9.90	4460	0.08	0.06	0.16	780	3.8	0.03	0.07	0.38	0.03	0.38	0.03	0.1	1330	0.43	0.03	0.16
3	60	12.42	9.40	4920	-	-	-	1240	2.2	-	-	-	-	-	-	-	815	-	-	-
4	80	12.47	9.37	4370	-	-	-	1060	2.0	-	-	-	-	-	-	-	1290	-	-	-
5	100	12.38	9.30	4040	<0.05	0.05	0.06	1190	1.0	0.02	0.12	0.16	0.02	0.42	0.01	0.2	1430	0.36	0.03	0.13
6	120	12.33	9.30	4280	-	-	-	1240	0.3	-	-	-	-	-	-	-	1120	-	-	-
7	140	12.40	8.89	4230	-	-	-	1010	0.4	-	-	-	-	-	-	-	1590	-	-	-
8	160	12.40	8.75	3420	-	-	-	925	0.4	-	-	-	-	-	-	-	1180	-	-	-
9	180	12.39	8.44	2580	-	-	-	744	0.3	-	-	-	-	-	-	-	758	-	-	-
10	200	12.45	7.93	2160	<0.05	0.01	0.06	520	0.3	0.02	0.08	0.22	0.03	0.32	<0.01	0.3	330	0.10	0.02	0.07
11	220	12.35	7.82	1990	-	-	-	617	<0.1	-	-	-	-	-	-	-	38.5	-	-	-
12	240	12.31	7.63	1850	-	-	-	617	<0.1	-	-	-	-	-	-	-	8.4	-	-	-
13	260	12.38	7.57	1890	-	-	-	617	<0.1	-	-	-	-	-	-	-	4.2	-	-	-
14	280	12.40	7.60	1840	-	-	-	573	<0.1	-	-	-	-	-	-	-	2.3	-	-	-
15	300	12.11	7.23	1820	-	-	-	521	<0.1	-	-	-	-	-	-	-	9.1	-	-	-
16	320	11.91	5.74	1500	-	-	-	353	<0.1	-	-	-	-	-	-	-	18.8	-	-	-
17	340	11.51	1.31	458	-	-	-	105	<0.1	-	-	-	-	-	-	-	47	-	-	-
18	360	11.43	0.87	364	-	-	-	78	<0.1	-	-	-	-	-	-	-	93	-	-	-
19	380	11.36	0.74	328	-	-	-	82	3.4	-	-	-	-	-	-	-	71	-	-	-
20	400	11.22	0.59	250	0.70	0.04	0.06	61	3.3	<0.01	0.05	0.24	0.01	0.30	<0.02	6.9	54	0.12	0.04	0.02
Trial 2																				
1	20	12.46	9.09	5080	0.07	0.10	0.20	1140	10.5	0.03	0.04	1.00	0.02	1.26	0.03	0.20	1310	0.08	0.03	0.11
2	40	12.46	9.01	4620	0.07	0.07	0.15	900	3.9	0.03	0.07	0.26	0.04	0.30	0.03	0.20	1300	0.42	0.03	0.12
3	60	12.42	9.40	4700	-	-	-	1240	2.7	-	-	-	-	-	-	-	1400	-	-	-
4	80	12.45	9.40	4450	-	-	-	1190	2.3	-	-	-	-	-	-	-	1520	-	-	-
5	100	12.38	9.34	4700	<0.05	0.06	0.05	1250	1.3	0.02	0.08	0.24	0.02	0.36	<0.01	0.20	1290	0.45	0.03	0.13
6	120	12.36	9.39	4180	-	-	-	1060	0.5	-	-	-	-	-	-	-	1770	-	-	-
7	140	12.40	8.92	3800	-	-	-	1100	0.3	-	-	-	-	-	-	-	1600	-	-	-
8	160	12.44	8.53	3120	-	-	-	864	0.6	-	-	-	-	-	-	-	160	-	-	-
9	180	12.38	8.44	2670	-	-	-	744	0.3	-	-	-	-	-	-	-	765	-	-	-
10	200	12.46	7.99	2270	<0.05	<0.01	0.05	595	0.5	0.01	0.07	0.22	0.02	0.26	0.02	0.40	337	0.08	0.02	0.07
11	220	12.37	7.84	1960	-	-	-	786	<0.1	-	-	-	-	-	-	-	41.8	-	-	-
12	240	12.39	7.22	1830	-	-	-	573	<0.1	-	-	-	-	-	-	-	12.3	-	-	-
13	260	12.34	7.59	1870	-	-	-	662	<0.1	-	-	-	-	-	-	-	5.8	-	-	-
14	280	12.34	7.59	1850	-	-	-	662	<0.1	-	-	-	-	-	-	-	5.3	-	-	-
15	300	11.99	7.43	1860	-	-	-	595	<0.1	-	-	-	-	-	-	-	5.3	-	-	-
16	320	12.00	5.89	1580	-	-	-	405	<0.1	-	-	-	-	-	-	-	5.9	-	-	-
17	340	11.62	1.74	494	-	-	-	128	<0.1	-	-	-	-	-	-	-	30	-	-	-
18	360	11.52	1.01	393	-	-	-	88	<0.1	-	-	-	-	-	-	-	61	-	-	-
19	380	11.35	0.80	340	-	-	-	84	2.0	-	-	-	-	-	-	-	67	-	-	-
20	400	11.23	0.64	282	0.70	0.03	0.04	66	7.0	<0.01	0.04	0.32	0.00	0.30	<0.02	6.90	52	0.14	0.04	0.02

All results given in mg/L except pH and conductivity (mS/cm).
Weight loss over 20 leaching cycles: 65.7% in Trial 1 and 65.0% in Trial 2.

TABLE A.5 RESULTS OF COLUMN LEACHING TESTS ON BED MATERIAL FROM RUN 831214E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Mn	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
3	2.23	12.17	8.97	4260	0.40	0.12	0.21	1400	167	0.03	0.16	24.0	0.04	17.0	<0.04	1.02	1320	11.0	<0.10	0.06
5	3.72	11.89	8.09	3890	0.09	0.02	0.17	1000	<1.0	0.03	0.11	13.0	0.06	14.0	<0.20	1.30	1180	5.60	<0.10	0.30
8	5.95	12.29	8.23	4180	0.04	0.39	1.14	1170	7.5	0.02	0.10	3.70	0.02	4.60	<0.20	1.10	-	5.40	<0.10	0.02
11	8.10	12.07	8.67	4140	<0.10	0.35	1.31	1290	5.8	0.03	0.09	5.50	0.02	8.70	<0.20	1.10	1210	4.20	<0.10	0.09
14	10.40	12.20	8.07	3560	<0.05	<0.05	0.13	1900	7.5	<0.02	0.11	1.79	0.04	4.43	<0.04	1.00	-	4.40	<0.10	0.02
17	12.60	12.32	8.09	3750	0.30	0.03	0.15	2600	-	0.05	0.12	3.20	0.02	4.20	<0.02	0.38	1180	2.60	<0.10	0.03
20	14.90	12.28	8.10	3950	0.09	0.02	0.03	1060	0.3	0.03	0.10	1.30	0.05	2.30	<0.10	0.90	-	2.30	0.09	0.02
26	19.30	12.07	8.05	3670	<0.05	<0.01	0.04	967	6.3	0.02	0.08	0.82	0.04	2.56	<0.01	0.20	1160	0.60	0.03	0.02
32	23.80	12.12	8.16	3450	0.17	0.04	0.01	1090	-	0.03	0.09	0.78	0.02	2.02	0.02	0.20	-	0.26	0.02	0.02
38	28.20	12.03	8.68	3550	0.04	<0.02	0.02	488	-	0.05	0.11	0.90	0.02	1.03	<0.05	0.18	-	0.50	<0.05	0.02
44	32.70	12.03	8.15	3410	<0.02	<0.02	0.02	434	1.2	0.05	0.18	1.10	<0.02	2.00	<0.05	0.21	-	0.50	0.06	0.02
50	37.20	12.07	8.26	3510	<0.02	0.02	0.02	482	1.8	0.05	0.20	0.60	0.14	1.30	<0.05	0.76	1220	0.50	0.09	0.03
56	41.60	12.06	8.19	3540	0.06	0.02	<0.01	459	3.4	0.04	0.15	0.70	0.06	1.32	<0.05	0.49	-	0.40	0.07	0.02
62	46.10	12.14	8.14	3480	0.20	<0.10	<0.10	348	1.8	0.04	0.13	0.45	0.04	1.05	<0.03	0.47	1150	1.01	<0.10	0.10
68	50.50	11.72	8.36	3430	0.20	0.10	<0.10	368	2.2	0.03	0.14	0.42	0.03	1.23	<0.03	0.24	-	1.24	<0.10	0.04
Trial 2																				
3	2.31	12.16	8.83	4090	0.12	0.05	0.26	1250	151	0.03	0.30	19.0	0.04	19.0	<0.04	0.86	1480	10.0	<0.10	0.04
5	3.84	12.32	8.38	4186	0.22	0.05	0.21	1360	30	0.03	0.08	6.40	0.04	12.0	<0.04	1.03	1150	6.10	<0.10	0.02
7	5.38	11.99	8.26	4030	0.09	0.03	0.13	1070	18.4	0.02	0.31	7.30	0.05	13.0	<0.20	1.30	-	5.70	<0.10	0.46
10	7.69	12.11	8.37	4120	<0.10	0.29	1.13	1290	10.7	0.02	0.11	3.20	0.02	6.60	<0.20	1.70	1360	5.30	0.10	0.03
13	10.00	12.45	8.85	3480	0.14	<0.05	0.14	1900	7.1	<0.02	0.12	1.95	0.03	4.13	<0.04	0.70	-	3.90	<0.10	0.03
19	14.60	12.30	7.97	3890	0.13	0.04	0.17	1010	0.4	0.02	0.08	1.40	0.03	2.30	<0.10	0.40	-	1.30	0.07	0.02
25	19.20	12.11	8.37	3430	<0.05	0.04	0.07	900	3.7	0.03	0.12	0.62	0.03	1.42	0.01	0.30	1150	0.42	0.01	0.03
31	23.80	12.17	8.59	3880	<0.05	<0.01	0.04	1160	6.0	0.02	0.10	0.46	0.02	1.32	0.02	0.30	-	0.28	0.03	0.02
37	28.50	12.19	8.43	3470	0.17	0.04	0.02	1140	-	0.03	0.12	0.70	<0.01	1.58	0.02	0.20	-	0.24	0.02	0.02
43	33.10	12.08	8.17	3360	<0.02	<0.02	0.02	446	1.2	0.05	0.18	1.00	<0.02	1.50	<0.05	0.49	-	0.40	0.06	0.02
49	37.70	12.30	7.84	3400	<0.02	<0.02	<0.01	444	1.4	0.04	0.12	1.10	<0.02	1.80	<0.05	0.47	1220	0.40	0.07	0.02
55	42.30	12.09	7.95	3390	<0.10	0.10	<0.10	394	2.2	0.03	0.11	0.69	0.03	1.55	<0.03	0.30	-	1.14	<0.10	0.06

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.6 COLUMN LEACHING TESTS ON BAGHOUSE MATERIAL FROM RUN 831214E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	Ba	B	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
2	1.51	11.96	22.7	18000	<0.1	1.03	0.63	489	5650	0.03	0.28	2320	<0.02	4200	<0.2	9.6	2240	9.2	<0.1	0.04
Trial 2																				
2	1.58	12.17	24.5	16400	0.30	1.75	0.62	683	5310	0.03	0.10	2700	<0.02	3560	<0.2	6.4	2300	9.3	0.10	0.04

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.7 RESULTS OF COLUMN LEACHING TESTS ON 1:1 MIXTURE OF BED AND BAGHOUSE MATERIALS FROM RUN 831214E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	Ba	B	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
3	2.21	12.43	12.83	6440	<0.10	0.36	0.06	2000	1160	0.06	0.12	440	0.02	669	<0.02	0.37	1550	9.7	<0.10	0.02
6	4.42	12.38	8.56	4150	0.10	0.25	0.01	876	20.9	0.02	0.09	168	0.02	175	<0.10	0.50	1390	6.2	0.06	0.02
9	6.63	12.38	6.84	3380	<0.02	0.05	<0.02	306	5.2	0.03	0.11	199	<0.02	175	<0.05	0.16	-	2.7	0.07	0.02
Trial 2																				
3	2.10	12.44	12.35	6760	<0.10	0.48	0.05	2680	1230	0.07	0.12	620	0.02	770	<0.02	0.48	1500	11.9	<0.10	0.03
6	4.37	12.37	8.57	4110	0.15	0.26	<0.01	880	16.1	0.02	0.07	168	0.02	179	<0.10	1.30	1390	6.2	0.06	0.02
9	6.55	12.19	7.84	3310	<0.02	0.02	0.02	330	-	0.04	0.06	193	<0.02	9.22	<0.05	0.65	-	3.7	0.06	0.02

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.8 RESULTS OF COLUMN LEACHING TESTS ON BED MATERIAL FROM RUN 840117E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
3	1.06	12.21	9.53	4320	0.12	0.05	0.24	1560	167	0.03	0.24	114	0.03	87.0	<0.04	0.74	1500	9.20	<0.10	0.07
5	3.10	12.29	9.04	3990	0.14	0.05	0.21	1200	12	0.28	0.17	47.0	0.03	34.0	<0.04	1.00	1060	5.80	<0.10	0.30
7	4.34	11.95	8.50	3900	0.10	0.03	0.13	1240	25	0.02	0.12	44.0	0.09	26.0	<0.20	1.20	-	5.10	<0.10	0.09
9	5.58	12.12	8.53	3890	0.19	0.06	0.14	1250	9.6	0.04	9.00	24.0	0.08	15.0	<0.20	1.30	1210	5.20	<0.10	0.10
12	7.44	12.21	8.00	4100	0.08	0.33	1.12	1100	4.0	0.02	0.08	20.0	0.02	13.0	<0.20	1.00	-	4.90	<0.10	<0.02
15	9.30	12.40	8.01	3670	<0.05	<0.05	0.16	1900	5.4	<0.02	0.12	14.0	0.03	11.0	<0.04	0.90	950	4.40	<0.10	0.02
18	11.20	12.06	7.99	3460	<0.10	0.06	0.16	2900	0.1	0.05	0.10	17.0	0.06	41.0	<0.02	0.24	-	3.10	<0.10	0.02
21	13.00	12.34	8.11	3750	<0.10	0.02	0.14	2700	3.9	0.05	0.12	8.00	0.08	6.30	<0.02	0.37	1410	1.80	<0.10	0.02
27	16.70	11.92	8.51	3450	0.08	0.04	0.05	832	2.9	0.03	0.11	4.00	0.03	3.94	<0.01	0.40	-	0.42	0.01	0.03
33	20.50	12.19	8.30	3500	0.10	0.01	0.03	1130	5.2	0.02	0.09	2.37	0.02	3.40	<0.01	0.20	1150	0.24	0.04	0.02
39	24.20	12.18	8.40	3700	0.08	0.05	0.08	803	<0.1	0.02	0.09	2.23	0.02	3.24	<0.01	0.20	-	0.31	0.09	0.03
45	27.90	12.28	8.51	3420	<0.02	<0.02	0.02	407	-	0.05	0.09	4.10	0.02	2.85	<0.05	0.34	-	0.40	<0.05	0.02
51	31.60	12.35	8.21	3440	<0.02	<0.02	0.02	449	0.6	0.04	0.14	3.30	<0.02	3.14	<0.05	0.24	-	0.40	0.06	0.03
57	35.40	12.31	8.32	3450	0.05	<0.02	0.01	464	0.6	0.04	0.14	3.60	<0.02	2.73	<0.05	0.39	1120	0.40	0.09	0.02
63	39.10	12.32	8.10	3520	<0.02	<0.02	<0.01	477	1.3	0.05	0.10	2.60	<0.02	2.21	<0.05	0.12	-	0.40	0.12	0.03
69	42.80	12.16	8.02	3630	0.45	0.05	<0.01	459	3.5	0.05	0.23	3.40	0.06	2.70	<0.05	0.24	1100	0.40	0.09	0.02
75	46.50	12.06	8.06	3390	0.20	0.10	<0.10	362	2.4	0.03	0.11	2.43	0.03	2.40	<0.03	0.24	-	1.12	<0.10	0.07
81	50.20	12.06	8.20	3430	0.20	0.10	<0.10	356	2.0	0.04	0.14	1.86	0.05	1.73	<0.03	0.43	1190	1.04	<0.10	0.05
Trial 2																				
3	1.92	12.23	9.23	4450	0.12	0.01	0.20	1250	174	0.03	0.22	102	0.03	83.0	<0.04	0.72	1500	9.30	<0.10	0.14
6	3.84	12.44	9.25	4040	0.20	0.05	0.20	1200	8.0	0.25	0.66	26.0	0.04	18.0	<0.04	0.62	2060	4.70	<0.10	0.05
8	5.12	12.10	8.34	3940	0.12	0.05	0.19	1040	9.4	0.02	0.13	45.0	0.06	29.0	<0.20	1.20	-	4.80	<0.10	0.22
10	6.40	12.15	8.46	3770	0.15	0.04	0.10	1090	10.4	0.03	0.62	32.0	0.04	16.0	<0.20	1.30	1180	5.30	<0.10	0.07
13	8.33	12.25	7.97	4120	0.06	0.56	1.37	1150	4.4	0.02	0.08	21.0	0.04	13.0	<0.20	1.00	-	4.00	<0.10	0.03
16	10.20	12.39	7.96	3580	<0.05	<0.05	0.14	1900	4.8	<0.02	0.12	13.0	0.04	11.0	<0.04	0.90	1260	4.40	<0.10	0.02
19	12.20	12.35	7.77	3330	<0.1	0.06	0.16	2000	5.9	0.04	0.08	14.0	0.02	12.0	<0.02	0.22	-	2.60	<0.10	0.02
22	14.10	12.20	8.02	3350	<0.1	0.02	0.14	2500	3.9	0.05	0.12	8.40	0.03	6.70	<0.02	0.56	1100	1.80	<0.10	0.02
23	17.90	12.07	8.26	3370	0.08	0.04	0.04	720	3.4	0.03	0.10	5.44	0.03	4.54	<0.01	0.20	-	0.52	<0.01	0.03
34	21.80	12.16	8.42	3740	0.06	0.01	0.03	1040	5.2	0.02	0.10	1.66	0.02	2.66	<0.01	0.20	1130	0.26	0.03	0.03
40	25.60	12.21	8.35	3500	0.05	0.06	0.08	930	<0.1	0.02	0.08	1.54	0.02	2.49	0.01	0.50	-	0.26	0.11	0.03
46	29.50	12.20	8.29	3440	0.16	0.04	0.01	1090	-	0.03	0.11	3.96	0.04	3.21	0.02	0.20	1140	0.24	0.02	0.03
52	33.30	12.25	8.25	3390	0.04	<0.02	0.02	395	-	0.07	0.10	3.60	0.12	2.80	<0.05	0.35	-	0.40	<0.05	0.04
53	37.10	12.27	7.45	3350	<0.02	<0.02	<0.01	390	2.0	0.04	0.25	5.70	<0.03	5.07	<0.05	0.36	1150	0.40	0.08	0.03
64	41.00	12.20	7.96	3770	0.03	0.05	0.02	466	3.4	0.06	0.24	3.40	0.23	2.54	<0.05	0.23	-	0.30	0.07	0.03
70	44.80	12.04	8.07	3320	0.40	0.10	<0.10	345	2.6	0.03	0.11	2.17	0.03	2.10	<0.03	0.20	1190	0.98	<0.10	0.04

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.9 RESULTS OF COLUMN LEACHING TESTS ON BAGHOUSE MATERIAL FROM RUN 840117E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
3	2.09	8.43	7.00	7170	1.10	7.87	0.55	1400	2540	0.03	0.24	36	1.27	73	<0.04	10.3	1250	7.40	0.02	0.02
5	4.02	8.75	2.41	2640	1.06	6.51	1.54	624	6.8	0.01	0.05	9.00	0.96	9.0	<0.20	11.0	1500	3.00	7.00	0.09
7	6.75	8.55	2.30	2520	1.00	2.10	0.34	533	12.3	0.02	0.10	8.00	0.80	658	<0.20	10.0	-	1.90	7.90	0.33
10	9.64	8.37	2.21	2460	1.00	3.40	1.32	600	5.1	0.01	0.05	4.00	1.02	8.4	<0.20	6.00	1660	1.40	6.00	<0.02
13	12.50	8.34	2.22	2540	1.12	0.70	0.10	1200	5.2	<0.02	0.07	3.66	0.47	7.5	<0.04	8.60	-	0.70	2.00	<0.01
Trial 2																				
3	2.04	8.24	7.27	7470	1.10	0.00	0.50	1510	2310	0.03	0.20	34.0	1.20	75.0	<0.04	12.7	1100	7.90	0.02	0.02
5	4.73	8.60	2.30	2580	0.97	5.35	1.35	574	42.7	0.02	0.59	6.20	0.97	11.0	<0.20	10.0	1450	2.60	7.00	<0.02
7	7.57	8.34	2.21	2560	1.00	5.12	1.59	602	7.6	0.01	0.04	6.60	0.96	10.0	<0.20	6.00	-	2.10	7.00	<0.02
11	10.48	8.20	2.32	2900	1.30	2.92	1.36	650	9.1	<0.01	0.03	4.70	0.67	11.0	<0.20	7.70	1550	1.40	5.00	<0.02
13	12.30	8.31	2.20	2530	1.16	0.60	0.17	1000	5.0	<0.02	0.06	2.92	0.49	7.26	<0.02	8.80	-	0.80	2.00	0.01

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.10 RESULTS OF COLUMN LEACHING TESTS ON 1:1 MIXTURE OF BED AND BAGHOUSE MATERIALS FROM RUN 840117E

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO	Sr	V	Zn
3	2.01	12.30	11.22	7830	0.10	0.04	1.06	3700	1470	0.10	0.10	141	0.02	163	<0.02	0.40	1470	10.0	<0.1	0.10

All results given in mg/L except pH and conductivity (mS/cm).
Note: Insufficient sample was available to conduct two trials.

TABLE A.II RESULTS OF COLUMN LEACHING TESTS ON BED MATERIAL FROM RUN 8311240

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Mn	Mo	Si	SO_4	Sr	V	Zn
Trial 1																				
3	1.64	12.27	7.86	4220	0.12	0.05	0.19	1560	113	0.02	0.20	26.0	0.03	9.50	<0.04	1.10	1350	9.40	<0.10	0.12
6	3.27	12.20	8.00	4650	0.10	0.02	0.19	1170	2.4	0.07	0.10	41.0	0.04	10.0	<0.20	1.30	1620	5.50	<0.10	0.33
9	4.91	12.24	8.14	3810	0.10	0.45	1.52	1000	5.3	0.02	0.07	7.70	0.04	3.40	<0.20	1.00	-	5.30	<0.10	0.02
12	6.55	12.23	8.59	4250	<0.10	0.10	1.35	1100	6.3	0.03	0.09	4.20	0.02	3.70	<0.20	1.10	1310	5.10	<0.10	0.02
15	8.19	12.46	8.82	3640	<0.05	<0.05	0.15	1900	5.4	<0.02	0.09	5.01	0.04	4.04	<0.04	0.80	-	5.20	<0.10	0.01
18	9.82	12.44	8.17	3390	<0.10	0.02	0.16	2000	7.2	0.06	0.12	3.20	0.02	2.90	<0.02	0.25	1020	3.70	<0.10	0.02
21	11.50	12.32	8.00	3620	<0.10	0.02	0.14	2600	4.0	0.06	0.12	3.20	0.02	2.50	<0.10	0.13	-	3.50	<0.10	0.03
27	14.70	12.33	8.20	3700	0.16	0.01	0.10	1070	0.9	0.02	0.11	1.60	0.03	1.60	<0.01	0.50	1230	2.00	0.06	0.02
33	18.00	12.18	8.15	3530	0.10	0.04	0.04	1040	6.9	0.02	0.09	1.50	0.03	2.94	0.02	0.30	-	1.32	0.01	0.02
39	21.30	12.31	8.52	3460	<0.05	0.04	0.00	1040	<0.1	0.02	0.10	0.64	0.03	1.23	<0.01	0.20	1210	0.56	0.10	0.02
45	24.60	12.19	8.28	3440	0.17	0.03	0.01	1090	-	0.03	0.09	1.00	0.02	1.39	<0.02	0.10	-	0.30	0.02	0.02
51	27.00	12.28	8.53	3410	0.09	0.07	<0.01	459	-	0.06	0.08	1.20	0.02	1.28	<0.05	0.29	-	0.50	0.05	0.03
Trial 2																				
3	1.65	12.23	8.78	4290	0.12	0.05	0.21	1200	209	0.03	0.10	30.0	0.04	11.0	<0.04	0.74	1350	9.20	<0.10	0.02
5	2.75	12.28	8.02	3940	0.20	0.02	0.20	1170	13	0.03	0.55	13.0	0.06	5.50	<0.04	0.90	1150	6.00	<0.10	0.03
8	4.40	12.17	8.22	3810	0.13	0.37	1.19	1140	27	0.03	0.22	24.0	0.04	7.70	<0.20	1.40	-	4.80	<0.10	0.04
11	6.05	12.21	8.79	4010	0.11	0.01	0.17	1170	11	0.03	0.10	11.0	0.03	4.70	<0.20	0.90	-	4.50	<0.10	0.23
14	7.70	12.21	8.09	4040	0.06	0.31	1.54	1160	4.8	0.03	0.05	5.90	0.02	3.70	<0.20	1.00	-	4.50	<0.10	<0.02
17	9.35	12.23	8.62	4210	<0.10	0.10	1.21	1260	6.4	0.03	0.09	4.20	<0.02	3.00	<0.20	1.20	1400	4.50	<0.10	0.02
20	11.00	12.43	8.07	3720	<0.05	<0.05	0.15	1700	5.5	<0.02	0.00	4.79	0.03	3.96	<0.04	0.60	-	4.60	<0.10	0.01
26	14.30	12.37	8.10	3650	<0.10	0.02	0.14	2600	4.4	0.07	0.10	3.20	0.03	2.80	<0.02	0.21	1260	4.40	<0.10	0.02
32	17.60	12.20	8.52	3470	0.07	0.03	0.05	832	4.0	0.03	0.11	1.40	0.03	1.56	<0.01	0.30	-	1.80	0.01	0.03
38	20.90	12.20	8.25	3360	0.09	0.03	0.05	832	3.5	0.03	0.12	1.30	0.03	1.40	<0.01	0.20	1250	1.30	0.01	0.03
44	24.20	12.16	8.57	3760	0.13	0.05	0.03	1020	6.3	0.02	0.09	0.63	0.03	1.02	<0.01	0.20	-	0.62	0.01	0.02
50	27.50	12.17	8.46	3570	0.07	0.12	0.15	970	<0.1	0.02	0.05	0.40	<0.02	1.10	<0.01	0.20	1240	0.70	0.40	<0.01
56	30.80	12.18	8.43	3490	0.17	0.03	0.09	1140	-	0.04	0.15	0.72	0.04	0.86	<0.02	0.20	-	0.20	0.02	0.03
62	34.10	12.40	8.04	3380	<0.02	0.02	0.02	400	-	0.04	0.10	1.40	<0.02	1.43	<0.05	0.52	1220	0.50	0.07	0.02
68	37.40	12.30	8.10	3450	<0.02	<0.02	0.02	434	0.6	0.05	0.15	1.30	<0.02	1.20	<0.05	0.30	-	0.40	0.06	0.02
74	40.70	12.32	8.13	3510	<0.02	<0.02	<0.01	434	1.0	0.04	0.19	0.80	0.02	0.75	<0.05	0.34	1140	0.30	0.06	0.02
80	44.00	12.10	8.13	3810	0.07	<0.02	<0.01	436	3.0	0.04	0.16	0.90	0.02	0.82	<0.05	0.10	-	0.40	0.10	0.02
86	47.30	12.06	7.54	3310	0.90	<0.10	<0.01	338	1.0	0.05	0.12	0.63	0.07	0.95	<0.03	0.47	1180	0.94	<0.10	0.05
92	50.60	12.11	8.12	3390	0.30	<0.10	<0.10	362	2.0	0.05	0.11	0.75	0.10	1.01	<0.03	0.50	-	1.10	<0.10	0.04

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.12 RESULTS OF COLUMN LEACHING TESTS ON BAGHOUSE MATERIAL FROM RUN 8311240

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO_4	Sr	V	Zn
Trial 1																				
2	1.56	12.33	10.41	5230	0.12	0.02	0.38	1250	879	0.03	0.16	406	0.02	125	<0.04	0.02	1410	9.00	<0.10	0.03
4	3.12	12.27	8.97	4090	0.00	0.24	1.60	952	43	0.02	0.13	440	0.04	98	<0.20	1.30	1560	6.50	<0.10	0.38
Trial 2																				
3	2.33	12.22	9.90	4900	0.14	0.04	0.52	1200	626	0.02	0.16	355	0.03	107	<0.04	1.0	1410	9.50	<0.10	0.04
5	3.89	12.17	7.62	4010	0.00	0.47	1.75	831	16.7	0.03	0.04	471	0.02	84	<0.20	1.3	1580	6.40	<0.10	0.02

All results given in mg/L except pH and conductivity (mS/cm).

TABLE A.13 RESULTS OF COLUMN LEACHING TESTS ON 1:1 MIXTURE OF BED AND BAGHOUSE MATERIALS FROM RUN 8311240

Cumulative Pore Volumes	Cumulative Liquid/solid Ratio	pH	Conductivity	Total Dissolved Solids	Al	B	Ba	Ca	Cl	Cu	Fe	K	Mg	Na	Ni	Si	SO	Sr	V	Zn
Trial 1																				
3	2.31	12.41	8.95	4610	<0.10	0.02	0.33	3100	64.7	0.07	0.14	88	0.04	22	<0.02	0.57	1510	13.20	<0.10	0.03
6	4.62	12.41	8.17	4370	0.26	<0.01	0.32	989	12.7	0.04	0.08	127	0.04	28	<0.10	0.60	1310	6.00	0.06	0.03
Trial 2																				
3	2.39	12.43	8.94	4600	<0.1	0.03	0.34	3300	68.7	0.05	0.12	106	0.03	21	<0.02	0.9	1550	12.50	<0.10	0.03
6	4.78	12.35	8.57	4450	<0.1	0.04	0.27	2800	13.2	0.04	0.12	125	0.02	25	<0.02	0.3	1310	8.60	<0.10	0.02

All results given in mg/L except pH and conductivity (mS/cm).